Report No. 2-32300/3R-53434
Contract NAS8-34678
9 May 1983

Development of Deployable Structures for Large Space Platform Systems

Volume 2

Technical Final Report

Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Alabama

By:

Vought Corporation
Dallas, Texas

LTV Vought

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R. L. Cox
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R. A. Nelson
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FOREWORD

This report describes an 18 month study of deployable structures for large space platform systems. The study was conducted by the Vought Corporation for the NASA George C. Marshall Space Flight Center. The work was performed under contract NAS8-34678 in two parts. Part 1 spanned the period 29 October 1981 through 31 July 1982; Part 2 covered the period 9 August 1982 through 9 May 1983. The effort was monitored by Erich E. Engler, COR, and W. E. Cobb, Co-COR of the Structures and Propulsion Laboratory. Dr. R. L. Cox of Vought was Study Manager of the program. Mr. R. A. Nelson performed conceptual and design studies and coordinated design effort. Mr. H. C. Allsup conducted interface design studies and deployable volume integration studies. Mr. G. M. Richards conducted design studies for the ground test article. Messrs J. B. Rogers, R. W. Simon, J. J. Atkins and J. E. Hyden performed structural analyses. Mr. C. A. Ford and P. Y. Shih conducted dynamic analyses. Mr. D. D. Stalmach carried out thermal and deployability analyses. Mr. J. A. Oren performed new technology and cost studies and directed thermal analyses. Materials studies were conducted by Mr. G. Bourland and Mr. M. W. Reed. Mr. G. L. Zummer performed studies for manufacturability. Mr. R. E. McPartland provided electrical design support.

The authors wish to thank the contributors mentioned above for their dedication and for the excellence of their support to this program. The authors also wish to thank Messrs Engler and Cobb for their guidance and support during this study, and Mr. J. J. Pacey of Vought for his valuable consultation and assistance. Special thanks is due to Ms. D. M. Fethkenher who provided secretarial, data management and publication services throughout the program.

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1.0 INTRODUCTION AND SUMMARY

Studies of future space applications show an emerging need for multipurpose space platform systems. Prior work has focused on the development of generic structural platforms and on point designs of systems for a few missions such as geostationary communications and scientific experiments. In order for the user community to realize the potential benefits of large structures for early 1990's missions it is important now to develop and demonstrate platform systems which offer both a high degree of versatility and which effectively integrate requirements for utilities, subsystems, and payloads. In addition, future missions such as a Space Station will require both pressurized and unpressurized volumes for crew quarters, manned laboratories, inter-connecting tunnels, and maintenance hangars. To minimize launch costs and enable use of volumes greater than those which can be transported by the Space Shuttle Orbiter, it is also desirable to evolve deployable volume concepts.

The current program was carried out in two parts. Part 1 involved the review, generation, and trade of candidate deployable linear platform system concepts with the selection of one of these concepts for further design and evaluation during Part 2, and the generation and screening of candidate concepts for deployable volumes. The objective of Part 1 of the program was to provide deployable platform systems concept(s) suitable for development to technology readiness by 1986. The systems concepts were based on trades of alternate deployable/retractable structure concepts, integration of utilities, and interface approaches for docking and assembly of payloads and subsystems. Further objectives were to identify material selection impacts and to identify special technology needs apparent in the concepts. The Part 1 objectives for the deployable volume studies involved generation of concepts for deployable volumes which could be used as unpressurized or pressurized hangars, habitats and interconnecting tunnels. Concept generation emphasized using flexible materials and deployable truss structure technology. Promising concepts were selected for subsequent study, their capabilities and limitations defined, and expected problem areas, design drivers and technology development requirements identified.

The objectives of Part 2 of the current program were to perform a layout design of a ground test article based on the results of the concept selection from Part 1. The design was to meet the specification for a prior

NASA-MSFC ground test article simulating a Science and Applications Space Platform (SASP) arm. Layout drawings were according to the Level 1 of Specification DOD-D-1000B. The design was of aluminum structure, derived from the Part 1 graphite/epoxy conceptual design of the selected Biaxial Double Fold concept. Also included in the ground test article design were analytical evaluations for both test and flight conditions. Deployable volume objectives during Part 2 were to evolve the selected Part 1 truss/bladder concept for the habitat and hangar modules. Included were selecting a specific truss concept for the habitat and hangar, minimizing the requirements for EVA during buildup, maintaining large deployed/stowed volume ratios, and conducting more detailed evaluations of crew accommodations, design characteristics, and Orbiter/Space Station compatibility. Additional objectives were to select and characterize single concepts for the habitat and hangar, and to identify special technology needs.

The elements of a deployable platform system are illustrated in Figure 1, adapted from the Reference 1 Definition Study of the Advanced Science and Applications Space Platform (ASASP). The core element of the

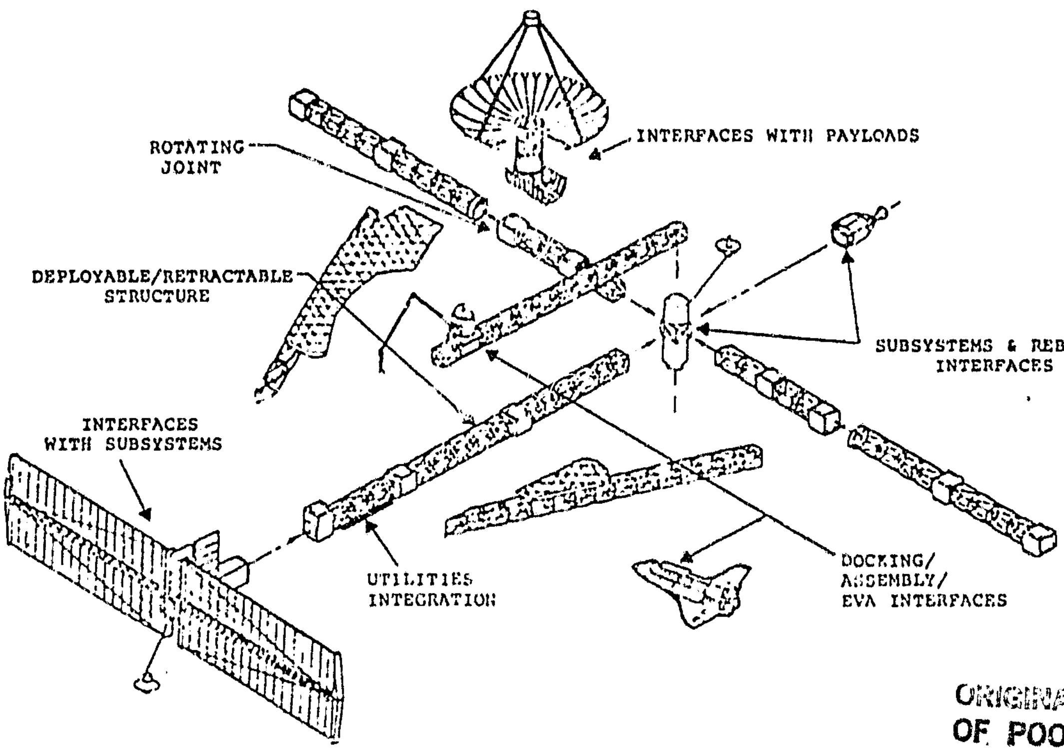

FIGURE 1 ELEMENTS OF DEPLOYABLE PLATFORM SYSTEM

deployable platform system is its automatic deployable/retractable structure. Some of the major interfaces are the spacecraft utilities, where full integration with the structure is desired, subsystems and payloads, docking, assembly, EVA, and various joints and attachments. All aspects of the interfaces are important influences to the deployable platform system design, including physical characteristics, imposed loads, dynamic interactions between the structure and attitude control subsystems, thermal distortion, payload stability requirements and deployment/assembly operations. Figure 2, from the Reference 2 Science and Applications Manned Space Platform (SAMSP), shows a typical Space Station concept and indicates three potential deployable volumes: an Orbital Transfer Vehicle (OTV) maintenance hangar, manned habitat/experiment module, and an interconnecting tunnel.

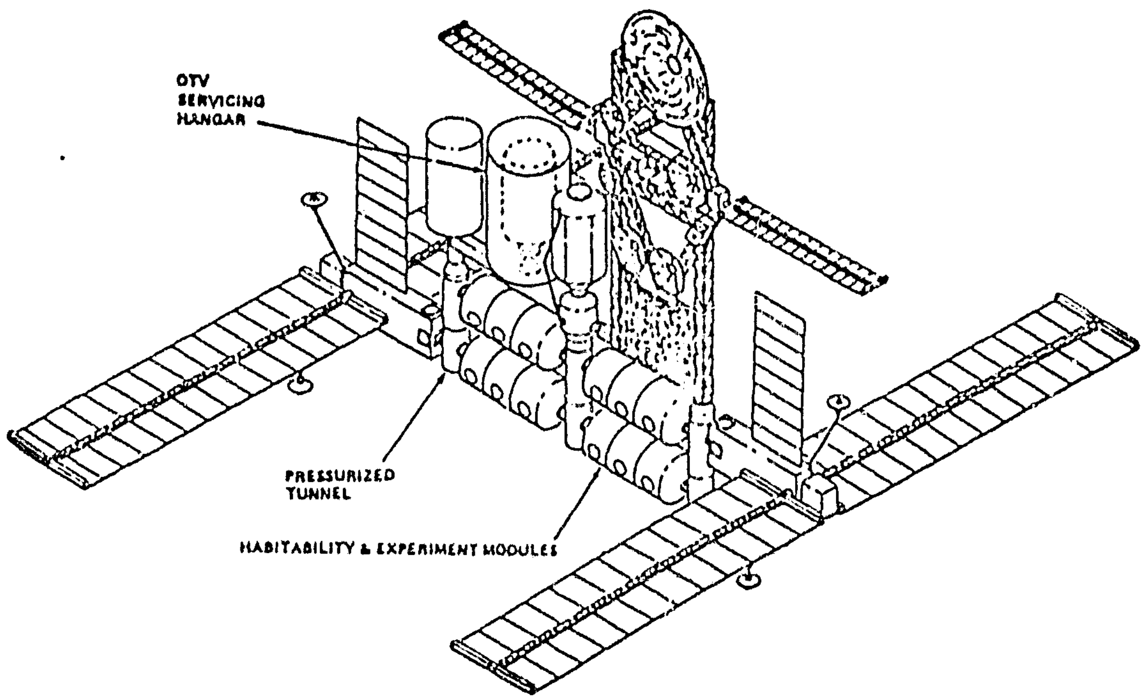

FIGURE 2 DEPLOYABLE VOLUME MISSION CANDIDATES

The study approach and work flow diagram for both Parts 1 and 2 are shown in Figure 3. Part 1 of the effort will be reviewed below in summary fashion. Reference 3 presents a comprehensive discussion of Part 1 results. The remainder of this report will concentrate on a detail presentation of Part 2 results.

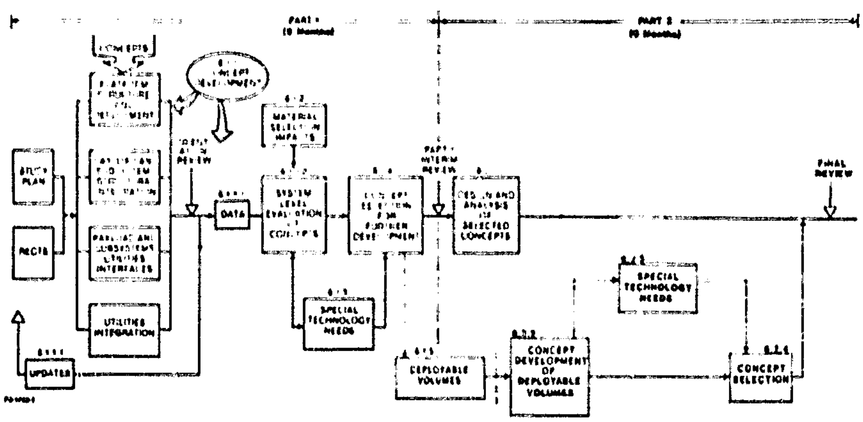

FIGURE 3

WORK FLOW

1.1 REVIEW OF PART 1 RESULTS

Results of Part 1 are summarized under two headings, Deployable Platforms and Deployable Volumes.

Deployable Platforms

The platform concepts are based on generic system requirements and selection critieria consistent with three focus missions:

Advanced Science and Applications Platform (ASASP)

Geostationary Communications Platform (GSP)

Solar Power Satellite Test Article II (SPS TA II)

These focus missions are defined in References 1, 4, and 5, respectively, and also in their prior supporting systems studies. In establishing generic requirements, these missions, as well as other activity on large space platforms available in the literature, were consulted. The approach was to identify available requirements from these documents, then develop other key information not available in the documentation as required. Four of the major areas in which requirements were determined included stiffness of the deployable truss structure, strength, utilities to be integrated into the truss structure, and interfaces. A parametric evaluation of stiffness requirements showed that beam bending stiffness values in the range 10^6 to 10^7 Nm^2 are required for small beams with a truss width of about 0.5 m. Stiffness requirements increase with beam size, reaching values in the range 10^8 to 10^9 Nm^2 for larger beams of 3 to 4 m width. Strength requirements for beams were also identified parametrically, and range from 10 to 10^4 Nm for the smaller beams up to about 10^5 Nm for large beams. Utility integration requirements range from a utility cross-sectional area of approximately 5 cm^2 for small trusses up to about 70 cm^2 for truss widths of 3 to 4 m.

Four generic types of interfaces were identified: truss-to-truss interfaces, truss-to-module interfaces, docking/joining interfaces, and truss-to-equipment/payload interfaces. Truss-to-truss interfaces involve joining two sections directly without a docking adapter. Joints such as butt joints, tee joints, lap joints, and cross joints were identified. Truss-to-module interfaces join a deployable truss section directly to a rigid section, such as a subsystem module, without a docking adapter. Docking/joining interfaces include transition structure and interface hardware such as a standardized docking adapter or a rotary joint. Finally, truss-to-equipment/payload interfaces (including secondary structure where required) join subsystem elements and payload items directly to the truss structure.

Based on study objectives, generic mission requirements, and study guidelines, the following deployable platform design objectives were established: auto deploy/retract; fully integrated utilities; configuration variability; versatile payload and subsystem interfaces; structural and packaging efficiencies; 1986 technology readiness compatibility; minimum EVA/RMS; and Space Shuttle operational compatibility. To meet these objectives five major issues were defined, alternatives considered, and the design approach established.

The first major issue was truss folding. The alternatives considered were single vs double fold. The approach adopted was double fold because of the importance of volume ratio and packing efficiency. It was also established that a truss configuration with a versatility for either folding capability would be preferable. The second major issue was utilities integration. The alternatives considered were fully integrated utilities with the bundles either internal or external to the struts (but routed adjacent to the struts), or partially integrated with reels or trays internal or external to the truss lattice. The approach adopted was to design for fully integrated utilities. However it was also desired to provide compatibility for attachment of strap-on utilities for "tall pole" missions. The third major design issue was payload integration. The alternatives considered were integration by a payload interface module vs payload interface directly to the truss. Because each of these alternatives have distinct advantages in certain design situations, the approach was to accommodate both. The fourth major issue was that of subsystem integration. The alternatives considered were integration by subsystem module vs integration directly onto the structure. Again there are advantages to either, and the approach chosen was to accommodate both alternatives. The fifth design issue was modularity, where the alternatives were a fully modular structure consisting of standarized building blocks vs a modular/scalable structure which had a standard scalable design. The chosen approach was to design for the modular/scaleable structure but not to preclude use as standard building blocks where this would be beneficial.

Conduct of the deployable platform systems study was initiated with the structural concept generation and evaluation effort. A large number of potential deployable truss candidates were identified and judgementally evaluated against Level "0" criteria and screened to eleven candidates, pictured in Figure 4. A more detailed evaluation and screening procedure was applied to the eleven. That resulted in a selection of four candidates, also shown in Figure 4. These were the Biaxial Double Fold (BADF), the Double Fold (DF), the Square Diamond Beam Truss (GDC), and the Box Truss (MMC). Each of these package compactly, offer good potential for automatic deployment/retraction and utilities integration, and have promise of versatility of application.

The next step of the deployable platform study was to conduct design and analytical trades on the four surviving truss concepts. These entailed design studies of utilities, subsystem and payload integration, and branching/assembly interfaces for evaluation of versatility for assembling

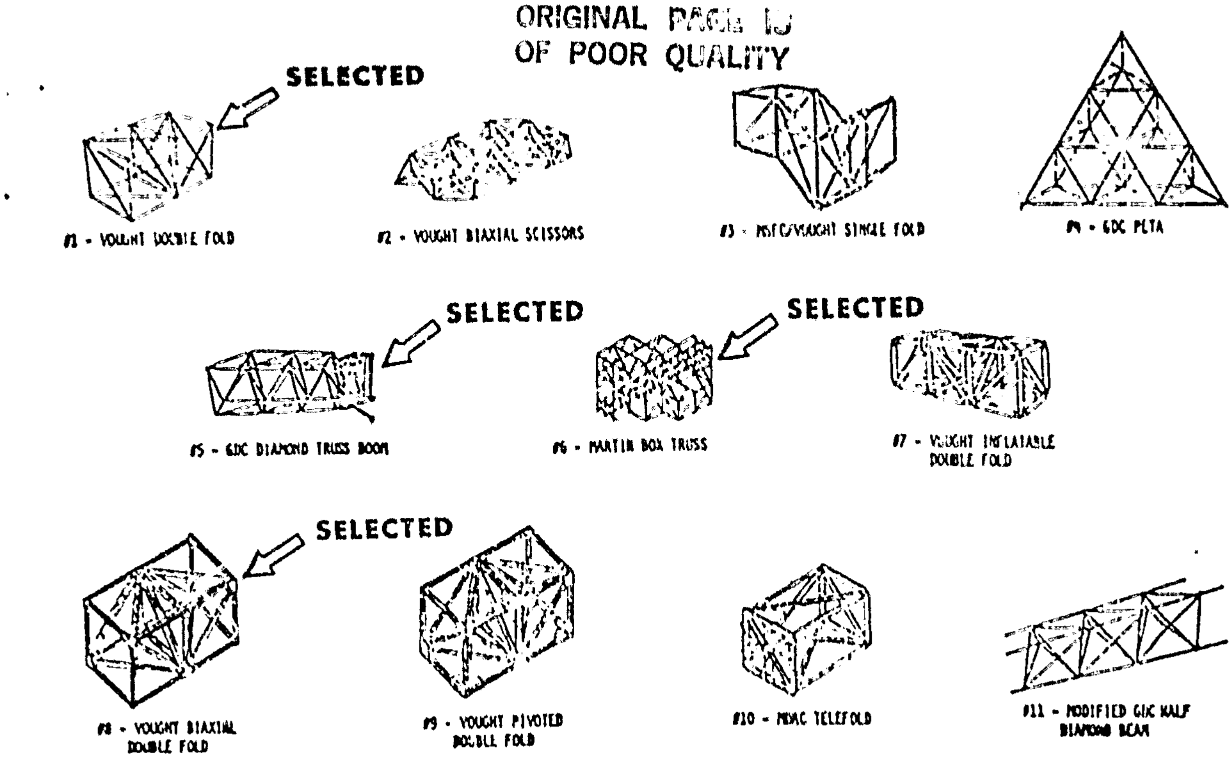

FIGURE 4 STRUCTURAL CONCEPTS EVALUATED

deployed modules. Parametric, structural, and thermal analyses were performed to support the trades and a materials selection study was conducted with the result that all structural sizing was carried out on a high modulus graphite/epoxy composite (GY70/934). Cost trades, which identified differences due to both fabrication and Shuttle launch, were also conducted . Based on the trade results each of the four deployable truss concepts was scored against 26 individual criteria relating to five major categories; platform capability, deployability, versatility, integration, and performance. Weighting factors were assigned and a final ranking was determined. The Biaxial Double Fold was clearly superior in each major category and it was found that the choice was not vulnerable to the assignment of weighing factors. It was thus selected for further definition during Part 2.

An overview of the characteristics and capabilities of the selected BADF concept is given by Figures 5 through 12. The general arrangement of a 3 meter square beam with utilities integrated inside the struts is summarized in Figure 5. The sketch also illustrates the folding

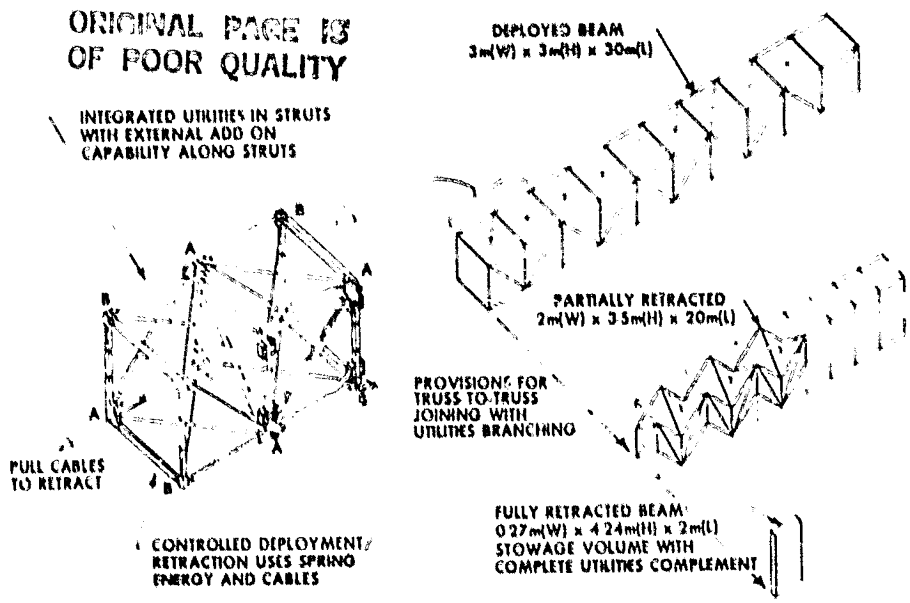

FIGURE 5

FEATURES OF SELECTED BADF STRUCTURE

scheme of the BADF. The truss folds simultaneously in two directions by telescoping the vertical struts and pivoting the bulkhead and side diagonals. All cells in the truss fold at the same time. This folding scheme minimizes the number of joints and the stowage volume. It results in a packaged height equal to diagonal length. Only two types of nodes are involved in the BADF concept; "A" nodes to which all diagonal struts are attached, and "B" nodes. Figure 5 also indicates the method used to energize the deployment and retraction. Deployment is by a combination of energy stored in linear springs located in the vertical struts and coil springs in bending located in the longitudinals and the laterals at the A nodes. Tension on the cable system provides the force for retraction and also an opposing force for control during deployment. A single reversible cable drive motor actuates the entire deployable truss. The figure also indicates the utilities integration approach, where a full complement of utilities for a large deployable platform such as the ASASP can be routed through the hollow longitudinal struts. Additional space is available for an equal quantity of add-on utilities mounted external to the longitudinal struts should that be desirable for some subsequent missions. Provisions for utilities and mechanical connectors, which will be necessary for branching of truss sections and payload interfaces, would be located on the sides or end of a truss section. Figures 6 and 7 are photographs of a model fabricated by Vought, approximately 1/10th scale relative to a 3 m beam. The photographs show the model in its fully retracted condition, followed by views in partial and full deployment. The deployed dimensions of the model are 112 cm in length and 28 cm square. The model is constructed of brass. The cable system for control and retraction is made from nylon fishing cable for the model.

Figure 8 shows how the Biaxial Double Fold truss may be used as an area platform. Illustrated is a square platform consisting of 10 rows and columns of cells, with overall dimensions of 25.9 m x 25.9 m x 2.6m. The diameter of the struts for this illustration is 5 cm. The retracted dimensions are 1.3 m x 1.3 m x 3.6 m.

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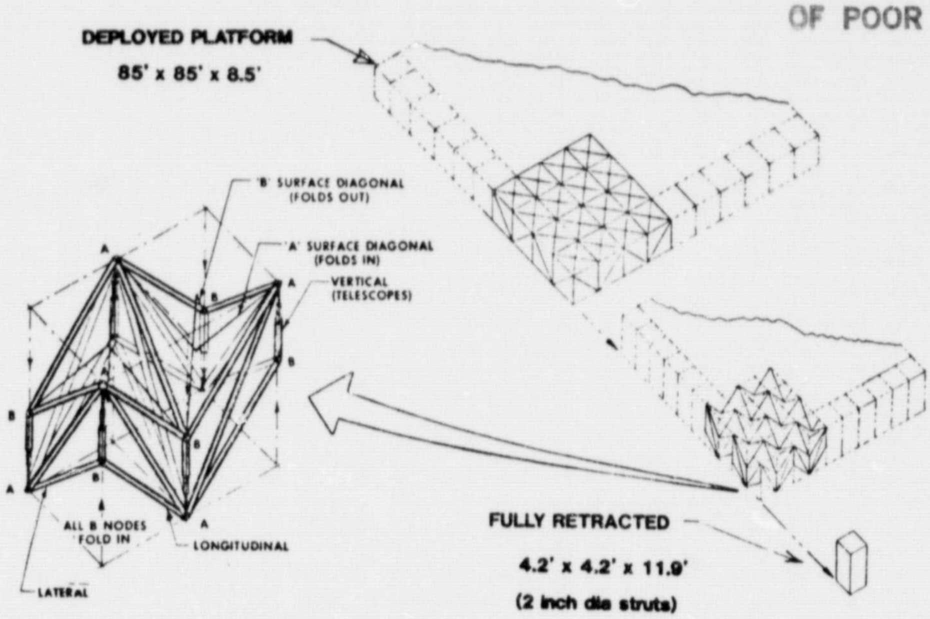
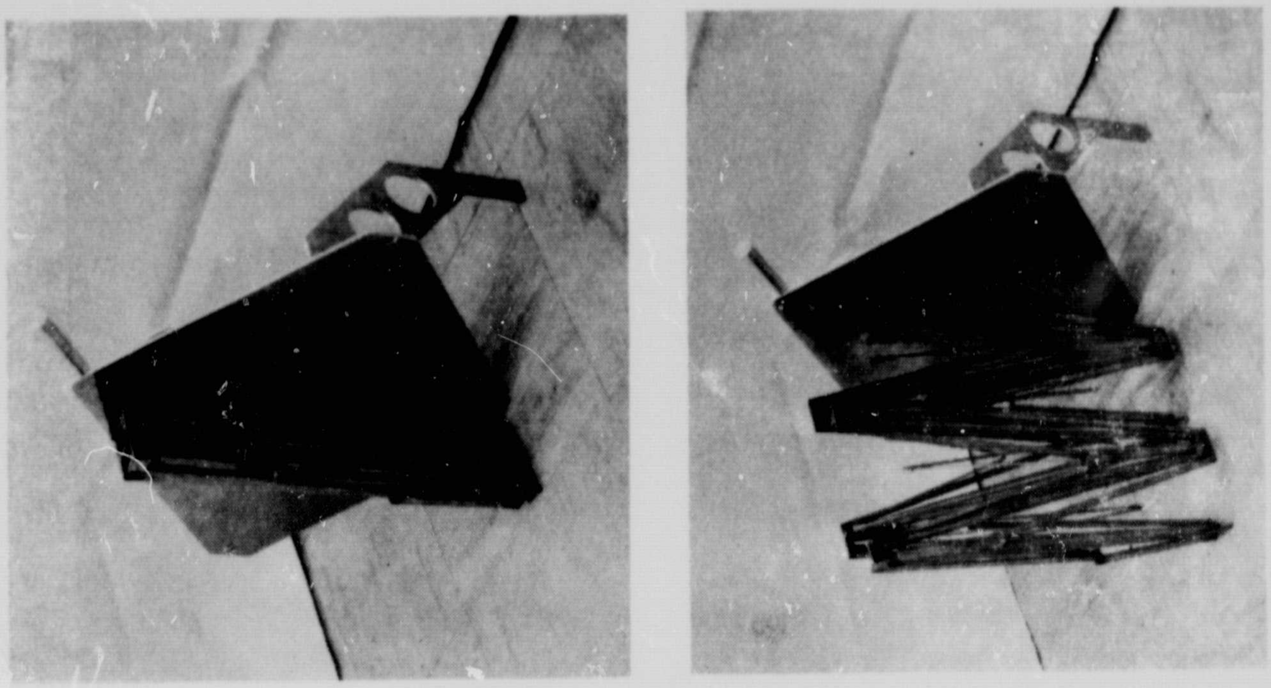


FIGURE 8

BIAXIAL DOUBLE FOLD AS AN AREA PLATFORM

Figure 9 summarizes the utility integration and interface concept. The representative utility bundles indicated were derived from ASASP requirements and provide some additional capabilities above that. The concept for routing of utilities through nodes is illustrated by the B node design sketched in the figure. The bundle bend radius to diameter ratio shown is about unity, which was the minimum value used in our design studies. This value was found to be acceptable from our element tests for both bending



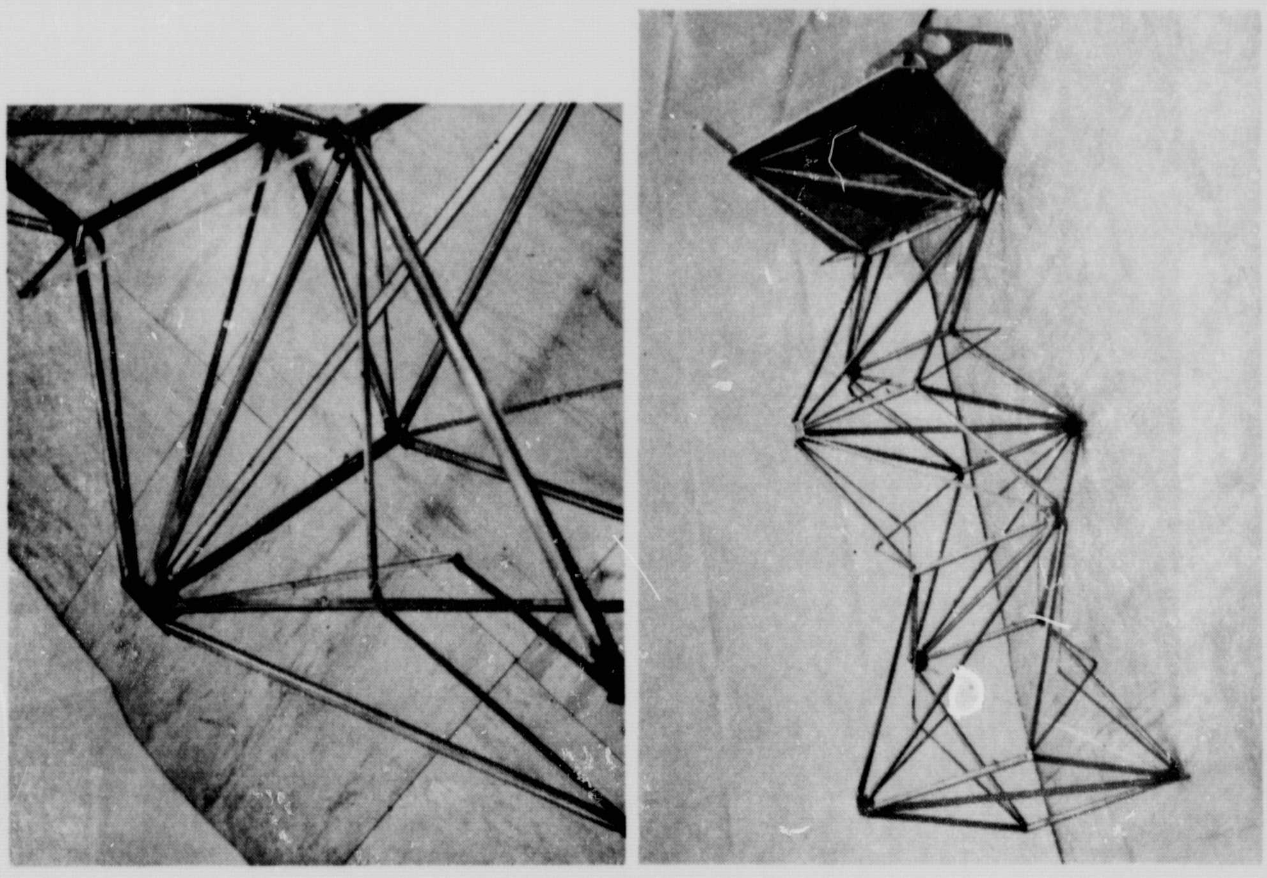


FIGURE 6
BIAXIAL DOUBLE FOLD TRUSS TENTH SCALE MODEL - INITIAL DEPLOYMENT

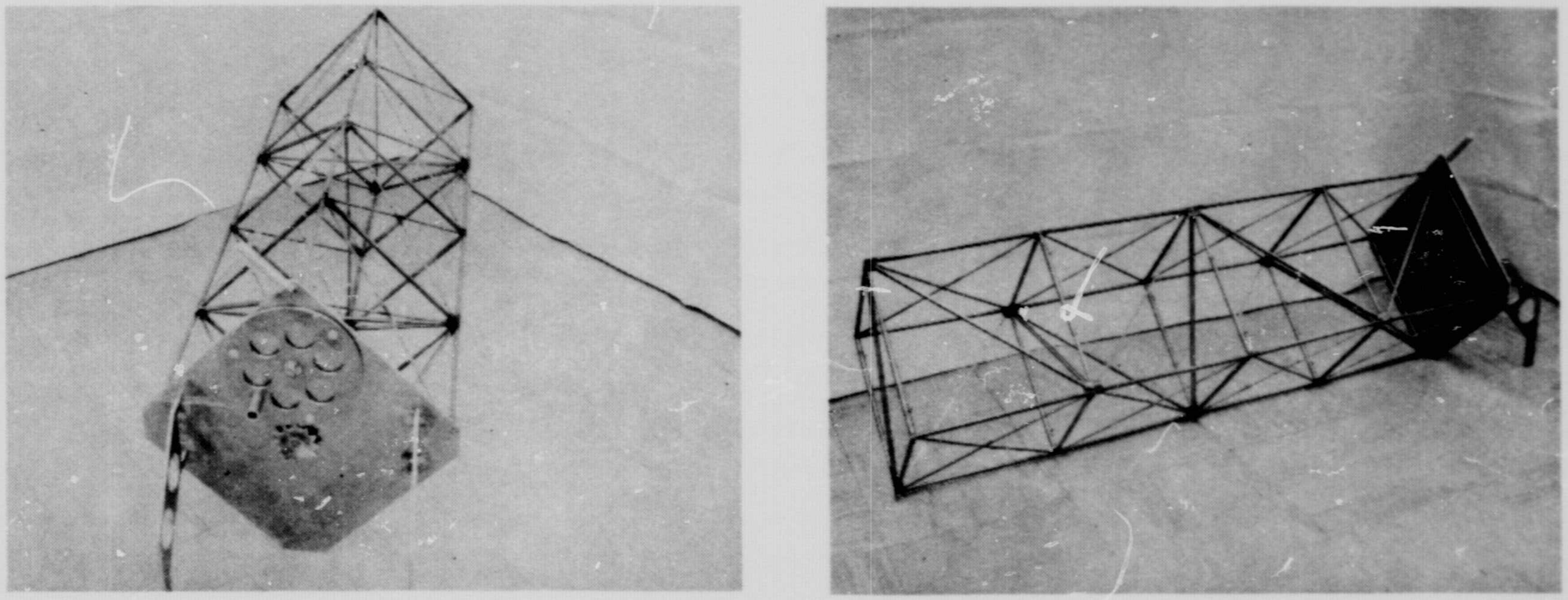


FIGURE 7
BIAXIAL DOUBLE FOLD TRUSS TENTH SCALE MODEL - FULLY DEPLOYED

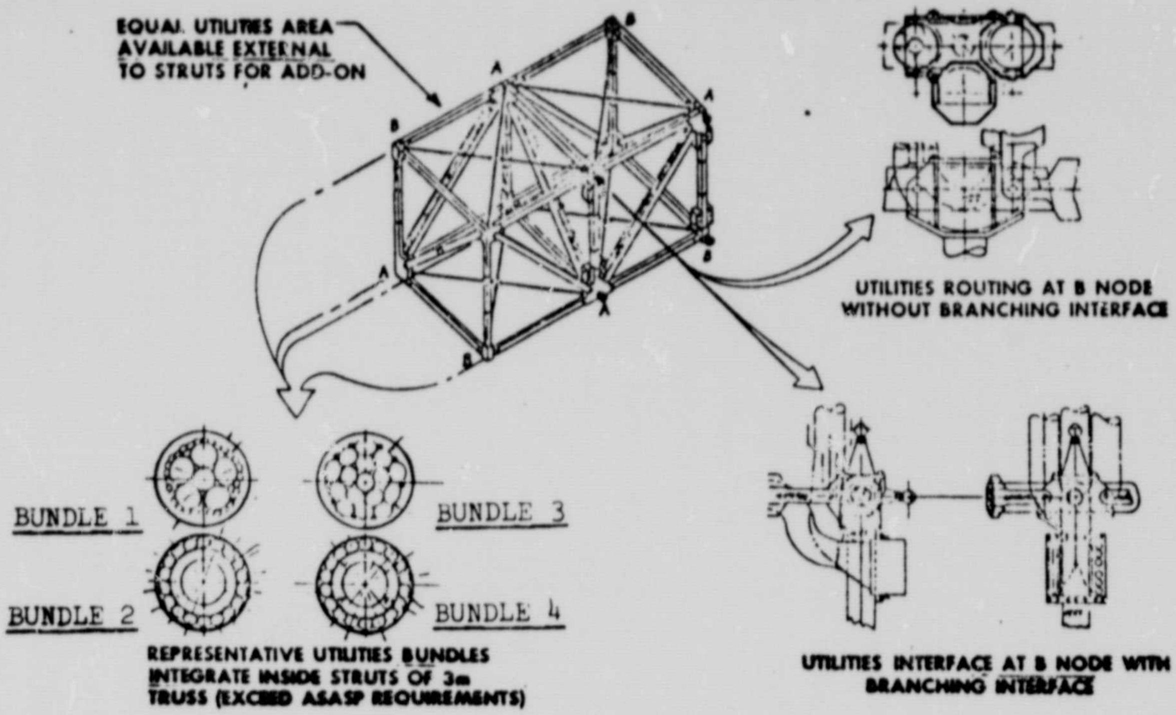


FIGURE 9

UTILITIES INTEGRATION CONCEPT FOR BADF

moment and cycle life considerations. The interface concept at a B node shows how utilities are branched from the opposite A node, routed through the bulkhead lateral strut, and then passed under the utility in the B node longitudinal to a floating connector fixed to the vertical strut. The interface concept at the A node is similar, only branching is directly from the A node rather than through a crossover from the opposite side of the truss.

Figure 10 shows the types of truss-to-truss and truss-to-module interfaces possible. With the interface design described in conjunction with Figure 9, the truss joining is accomplished in two steps. First the truss branches to be joined are maneuvered together using the RMS until capture and hard lock is accomplished at four nodes by the mechanical node-to-node Autolock Coupler. Second, an electrically powered ultility connector plate, not shown, pulls together the connectors with the aid of alignment pins, completing the mating operation. As indicated in Figure 10, various types of square, oblique, and size-change interfaces are possible without the addition of separate interface structure. This results from the peculiar capability of biaxially deploying trusses to intregrally deploy oblique or size-change transition structure.

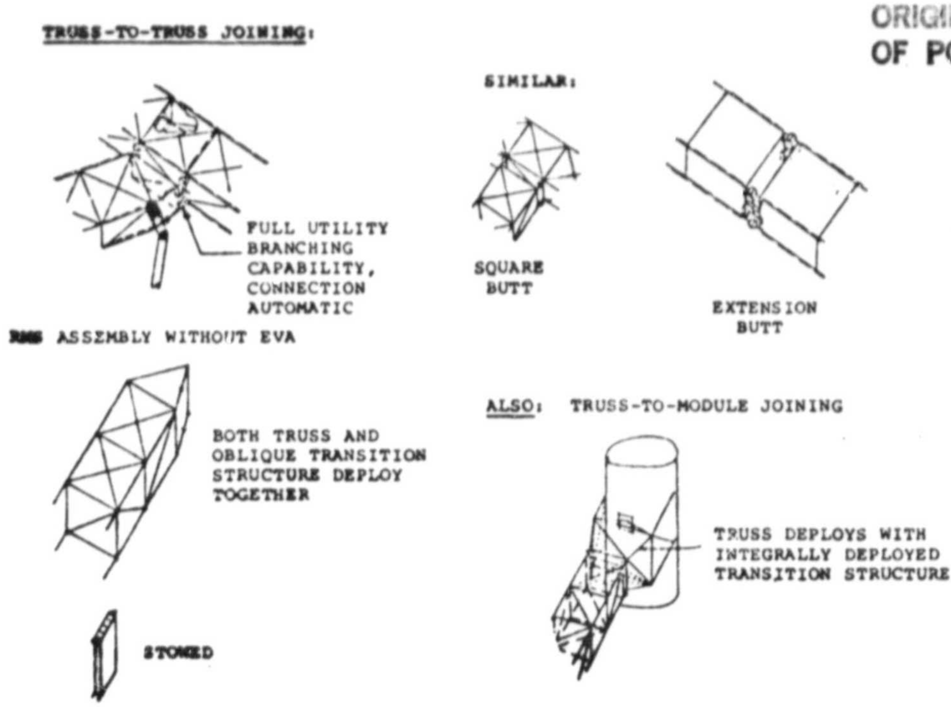


FIGURE 10

MODULE DEPLOYMENT ASSEMBLY WITH BADF

Figure 11 illustrates the capability of the BADF truss to be directly deployed or assembled into a variety of shapes. For example, the

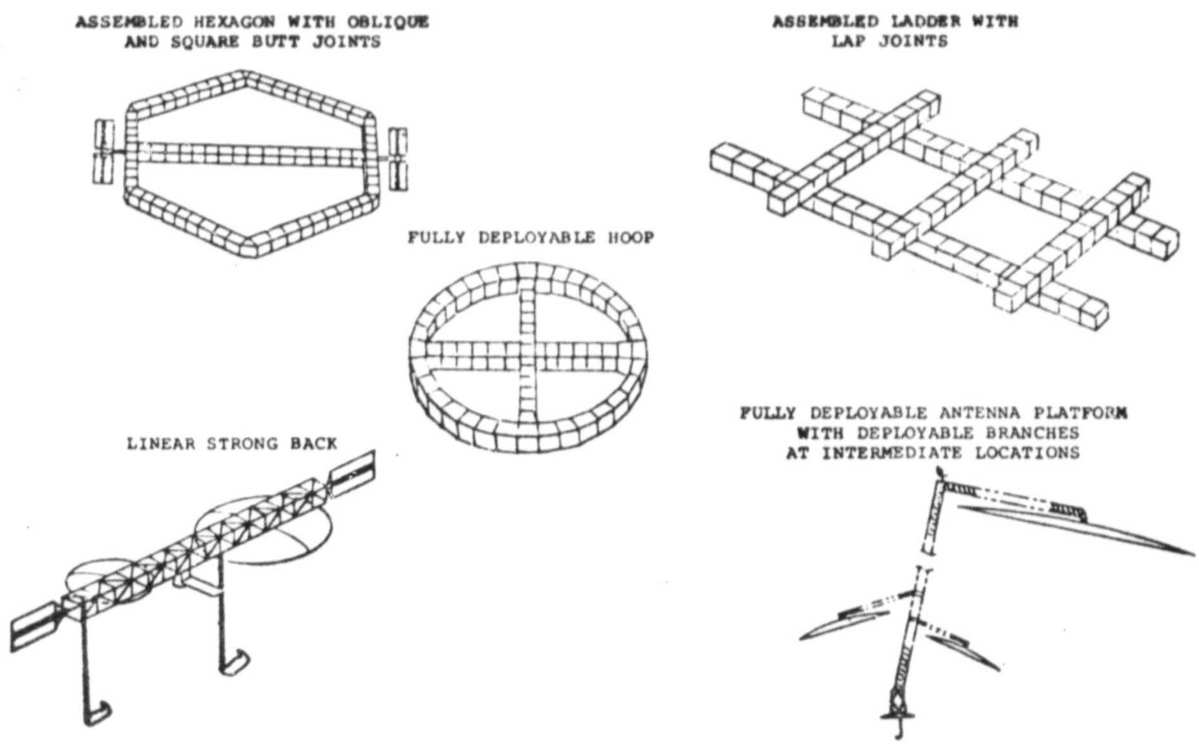


FIGURE 11

CONFIGURATION VARIABILITY OF BADF

indicated fully deployable hoop folds into a diameter of about 1/20th of its deployed diameter. This characteristic also makes the BADF a candidate for deploying volume shapes. Another useful capability is its ability to be deployed as a mast with intermediately situated payloads or deployable branch arms preattached and deployed simultaneously.

Figure 12 illustrates a mast experiment that can be flown in the Space Shuttle using the BADF design. Illustrated on that figure are the characteristics for a 50 cell, 100 m long redeployable mast packaged in the

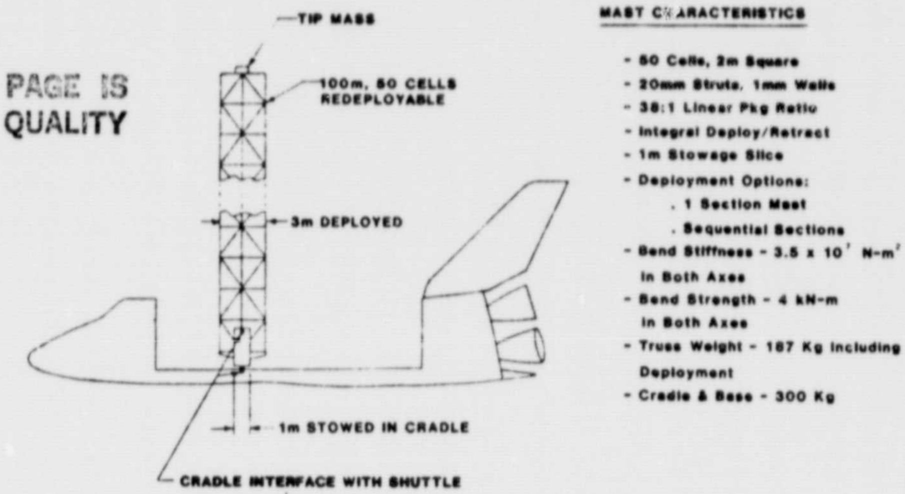


FIGURE 12

BADF MAST EXPERIMENT

Space Shuttle. The packaging requirements are also indicated. One advantage of the folding characteristics for the BADF are that it can be stowed in a 1 m length in the Shuttle cargo bay. This short stowage dimension provides advantage in the manifesting of a Shuttle flight.

The following conclusions are summarized from the Deployable Platform Part 1 studies:

1. The deployable platform system with fully integrated utilities and subsystem/payload interfaces is feasible.
2. The Biaxial Double Fold truss is the clear choice of four leading candidates.
3. Automatic deployment and retraction in a self-contained system can be achieved.

4. The Biaxial Double Fold design provides typical storage ratios of 172:1 for a 3 m truss with full utilities. Ratios as high as 300:1 are possible with minimal utilities.
5. Utilities integrated inside truss struts with interfaces for branching are possible. Equal space for growth external to struts also exists.
6. Small payloads/subsystems may be preattched locally to the truss. Large items may interface through berthing hardware which may be preattached.
7. Truss-to-truss interfaces and integrally deployed transition structure provide a wide variety of building block configurations.

Deployable Volumes

Several types of deployable volumes were considered in the concept identification task. Table 1 summarizes the concepts, their potential applicability, indicates their principal characteristics and limitations, and identifies those selected for evaluation. The most promising concept for manned habitat and OTV hangar applications was found to be a deployable truss approach with a bladder for pressure containment and an external thermal/meteoroid blanket. Two flexible concepts were identified as offering potential for tunnels: a convoluted design and an inflated cylindrical shell design.

Figure 13 illustrates the recommended concept for the deployable habitat. It consists of a deployable truss structure to which a

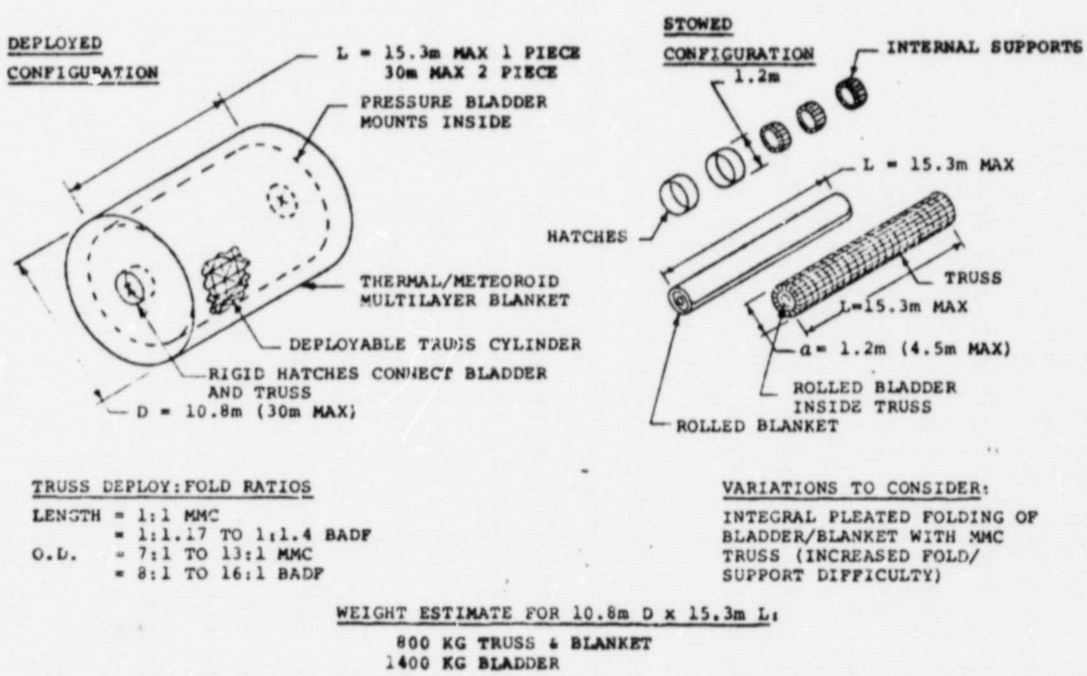
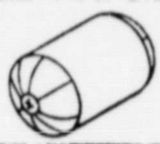
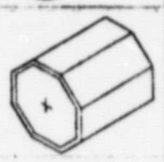
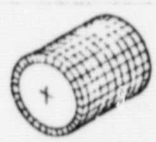
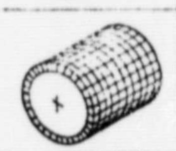


FIGURE 13 RECOMMENDED CONCEPT FOR HABITAT

TABLE 1

DEPLOYABLE VOLUME CONCEPTS CONSIDERED

CONCEPT		POTENTIAL APPLICATION			REMARKS
		TUNNEL	HABITAT	HANGAR	
TELESCOPING TUBES		√	---	---	. CABLES IN PARALLEL ADJUST LENGTH . ROLLING DIAPHRAGM SEALS . AIR LOCK OPTIONAL ON SMALL END . SIMILAR TO SHUTTLE DOCKING MODULE . NOT SELECTED TO PURSUE
FLEXIBLE CONVOLUTED TUBE		√	√	---	. RIGIDIZED BY FRAMES & LONGITUDINAL CABLES . CABLES ADJUST LENGTH/CURVATURE . 4.5m MAX DIA, 120m MAX LENGTH . SELECTED TO EVALUATE
FLEXIBLE STRAIGHT TUBE		√	√	√	. UNITIZED STRUCTURES - NO FRAMES/CABLES . NO DEPLOYED SIZE ADJUSTMENT . AS BLADDER FOR HANGAR OR HABITAT WITH INTERNAL/EXTERNAL SUPPORT STRUCTURE . SELECTED TO EVALUATE
FOLDING PANELS		√	√	---	. LOW DEPLOY : STOW RATIO . MANY SEALS IF PRESSURIZED . TOO SMALL FOR OTV HANGAR . NOT SELECTED TO PURSUE
RIBS AND BACKBONE		---	---	√	. UNPRESSURIZED HANGAR . THERMAL/METEOROID PROTECTION BLANKET . BACKBONE TRUSS & RIBS FOLD . MINIMAL STIFFNESS & WEIGHT STRUCTURE . NOT SELECTED TO PURSUE
DEPLOYABLE TRUSS SEPARATE BLADDER		√	√	√	. BADF OR MMC RIGID TRUSS SUPPORT . THERMAL/METEOROID BLANKET SPACED FROM BLADDER BY TRUSS . BLADDER & BLANKET ATTACHED AFTER DEPLOY . SELECTED TO EVALUATE
DEPLOYABLE TRUSS ATTACHED BLADDER		√	√	√	. MMC TRUSS FOR CONSTANT LENGTH . BLADDER & BLANKET DEPLOYED WITH TRUSS . SELECTED TO EVALUATE

thermal/meteoroid protection blanket is added on the outside and a pressure bladder on the inside. This type of deployable volume is applicable to a truss that is bidirectionally deployed, such as the BADF or the MMC Box Truss. When the deployed volume is folded it shrinks both in diameter and in the thickness of the truss structure. The length of the stowed Box Truss is the same as its deployed length, while the BADF is 17% to 40% longer. The pressure bladder stows inside the folded structure. It is possible to obtain a 13:1 or 16:1 diameter ratio when deploying the truss structure for the MMC or BADF, respectively. This enables a much larger Space Station module volume to be used within the diameter constraints of the Space Shuttle cargo bay than would be possible with a rigid structure. The deployment and assembly sequence first involves expansion of the stowed structure, then the bladder is secured, and next the interconnecting hard structure for the equipment internal to the deployed volume is added. Following that, external subsystems are installed through access doors in the thermal/meteoroid blanket. Internal equipment has to be added through the entrance hatch and, therefore, must be of a size that can be inserted through the hatch, or it must be deployable. Internal structure, such as decks, is assumed to be deployable structure and would be deployed subsequent to insertion into the volume. It is possible to simultaneously deploy the cylindrical section and the flat end part. It may also be possible to preattach the bladder internal to the structure and deploy the two simultaneously. Similarly, it may be possible to preattach the thermal/meteoroid blanket on the outside of the structure.

In the deployable volume concept all the pressure loads from the bladder are taken as hoop tension in the bladder itself. The truss structure and associated hanrdware serve as the interface with Space Station structure, as well as a mounting platform. Figure 14 shows the flexible straight tube concept for the bladder as developed by Goodyear in Reference 6. The photograph shows that the cylinder is collapsed in an axial direction similar to that of the convoluted tube. However, it can also be folded and collapsed in the diameter direction. For the habitat module and hangar concepts, it was evaluated as a bladder with no load carrying requirements other than the pressure load itself.

A utility integration concept compatible with the deployable truss and bladder volumes is illustrated in Figure 15. A subsystem can be placed

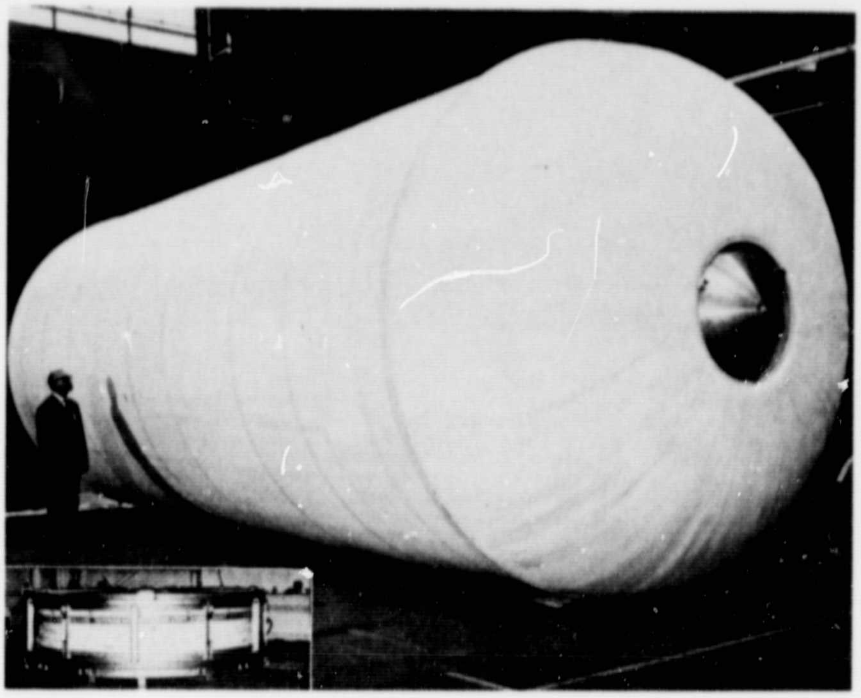


FIGURE 14

GOODYEAR MOBY DICK FLEXIBLE TUNNEL

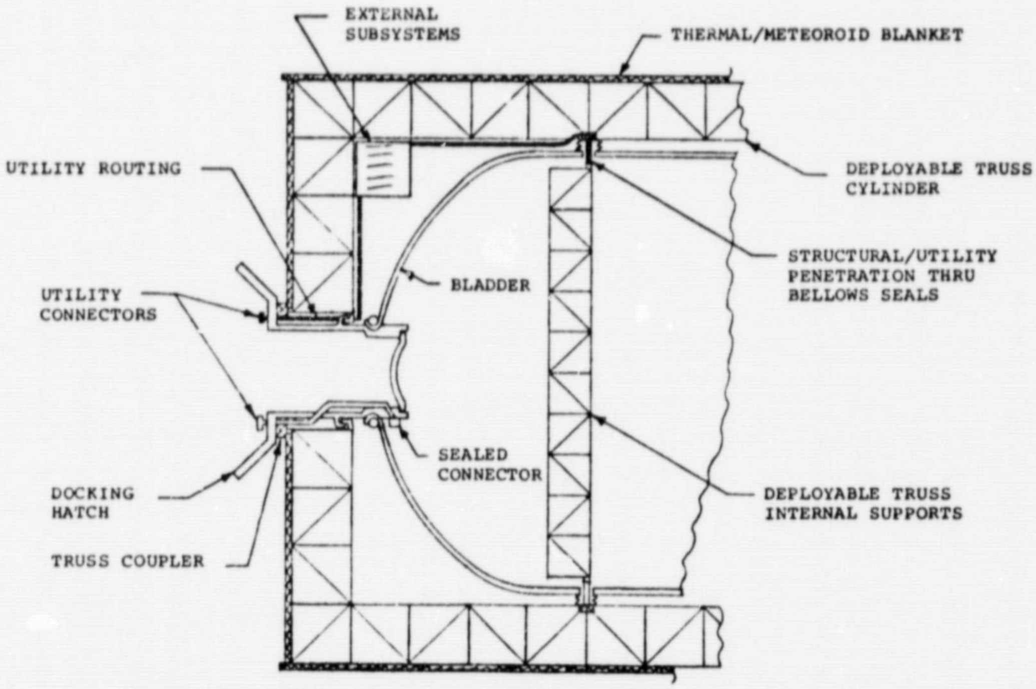


FIGURE 15

UTILITIES CONCEPT DETAILS

inside the external truss or located anywhere on it and be protected by the thermal/meteoroid blanket. Access is through the blanket flaps. Subsystems are installed with the aid of the RMS or EVA after deployment of the truss. The utilities paths are through the docking hatch directly to external subsystems or through the docking hatch into the pressurized compartment. Utilities from external subsystems interface equipment inside the pressurized compartment through the structural/utility bladder penetration, also indicated. A concept for hard point penetration of the bladder using a bellows seal is shown. It would be possible to evolve this concept to allow utilities feed through. Figure 16 shows the deployable truss volume concept rendered as an OTV hangar. In order to obtain the necessary length the structure is deployed in two sections. As indicated in the figure, the two sections are linked together similar to a clam shell. For a pressurized hangar a pressure bladder with a seal at the door interface will be provided; for a unpressurized hangar, no bladder is required. With a pressurized hangar concept stowage of the bladder involves collapsing the seal frame into a folded structure and rolling it inside the pressure bladder. This requires insertion of the bladder into the volume after the volume has been deployed, using EVA and the RMS. The OTV could be docked into the structure at one end. Other docking concepts could be used such as a track or rail down the side of the interior of the deployed volume.

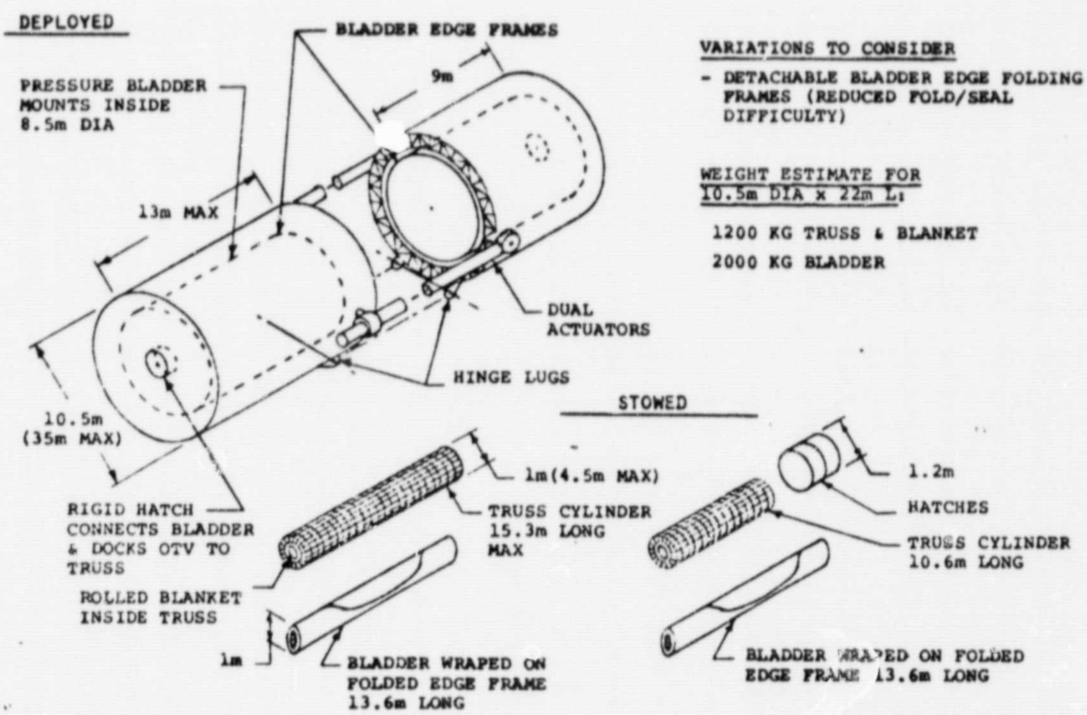


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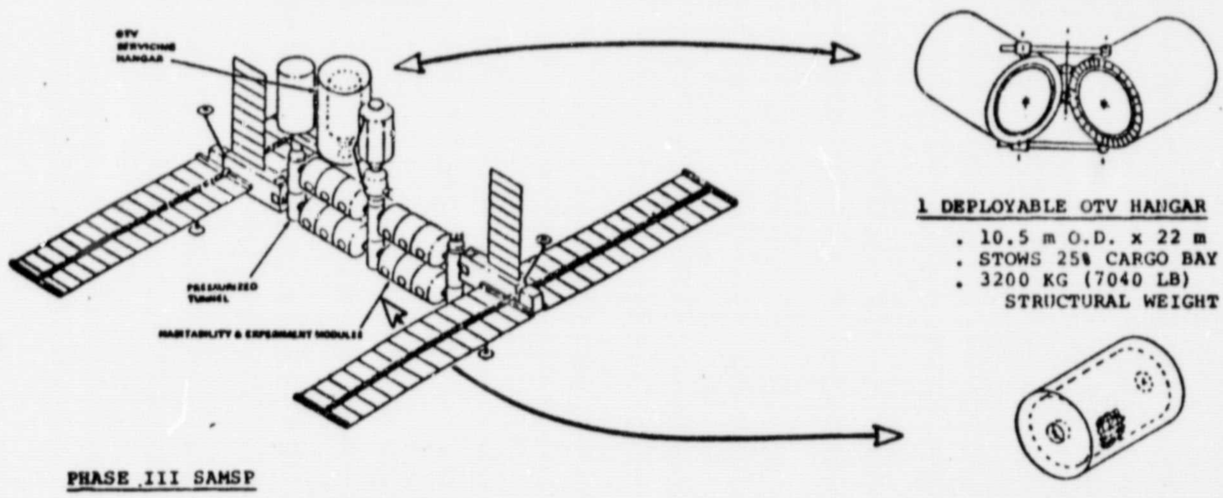
FIGURE 16

RECOMMENDED CONCEPT FOR OTV HANGAR

The flexible convoluted tube concept, indicated in Table 1, was also recommended for further study. It also was based on a concept developed previously by Goodyear and has been demonstrated in scaled prototype form. Volume ratios up to 8:1 can be obtained with this flexible tunnel in actual deployment. In order to provide loading carrying capability, it could be provided with an external axially folding truss, which would also provide a mounting for utility integration and support of a long life thermal/meteoroid blanket.

Figure 17 summarizes the potential benefits of a deployable volume concept to the NASA-MSFC Phase III Science and Applications Manned Space Platform (SAMSP). In the original SAMSP concept five Shuttle launches are required to place the four habitability/experiment modules and OTV hangar into orbit. The figure shows that a greater volume of habitability/experiment space plus an OTV hangar can be launched dry in one-half of one Shuttle flight using deployable volumes. The equipment used to outfit the deployable habitat/experiment module, packed at the same density as in the four baseline rigid modules, can be transported in somewhat less than one and a half Shuttle

RIGID MODULES **VS** **DEPLOYABLE VOLUMES**



PHASE III SAMSP

4 HABITAT & EXPERIMENT MODULES:
- STRETCHED SPACELAB MODULES, 10.1m (33.3 FT)
- 457 m^2 (16,150 FT^3) PRESSURIZED VOLUME
- 13,800 KG (30,300 LB) STRUCTURAL WEIGHT

1 OTV HANGAR (ERECTABLE OR DEPLOYABLE)

5 SHUTTLE FLIGHTS

1 DEPLOYABLE HABITAT/EXP. MODULE
. 10.8 m O.D. x 15.3 m
. STOWS 25% CARGO BAY
. 670 m^2(23,600 FT^2) PRES. VOL.
. 2200 KG(4840 LB) STRUCT. WT.

1/2 CARGO BAY FOR DEPL. VOLS.
1-1/2 CARGO BAY FOR TUNNELS, SUBS., EQP.

2 SHUTTLE FLIGHTS

FIGURE 17

DEPLOYABLE VOLUME LAUNCH BENEFITS

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flights, thus the total requirement for the deployable modules is two Shuttle flights compared to five for the equivalent baseline SAMSP modules. A systems trade would be necessary to determine the overall advantage considering the EVA/IVA operations necessary to outfit the dry deployable volumes with equipment.

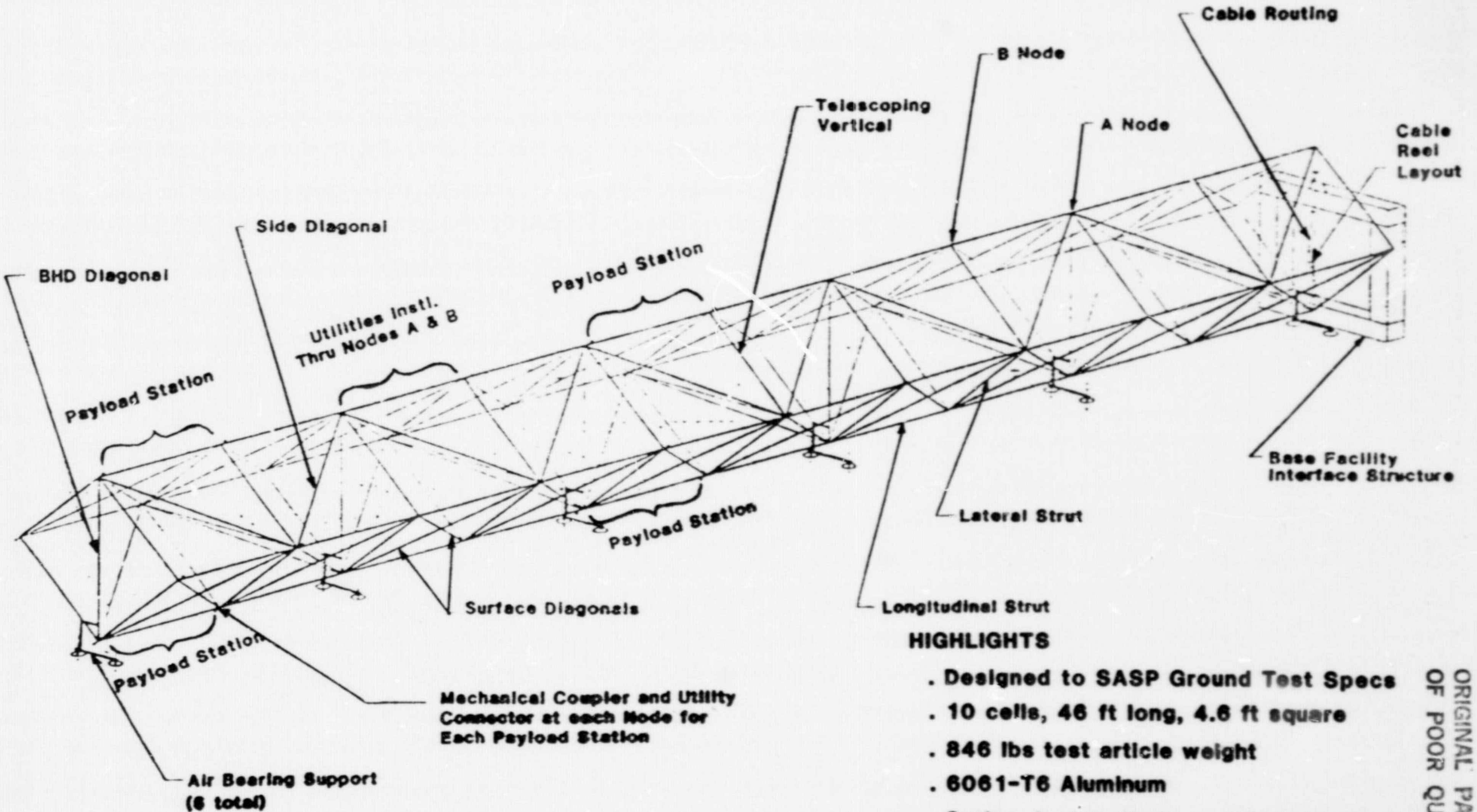
Conclusions from the Part 1 Deployable Volume study were that the concept featuring a flexible pressure bladder and a deployable truss structure leads to highly efficient candidates for habitat and hangar modules. Volume ratios up to 200:1 appear feasible. A representative 10.8 m outside diameter, 670 m^3 pressurized volume habitat weighs about 2200 kg including bladder, truss, and thermal/meteoroid blanket. It requires approximately 25% of the Shuttle cargo bay for delivery when delivered dry with major subsystems equipment added after deployment. Only about 1-1/2 to 2 Shuttle flights are required for delivery of both the hangar and habitat module and equipment. The biaxially folded design with either the BADF or the MMC Box Truss are leading candidates for the truss structure for deployable volumes.

A second major conclusion is that the flexible convoluted tube is the leading candidate for a deployable transfer tunnel. It should be considered with an added external truss structure to support utility integration and long life thermal/meteoroid blankets, as well as to provide a load carrying capability.

1.2 SUMMARY OF PART 2 RESULTS

Ground Test Article Design

Figure 18 is an isometric sketch illustrating the BADF ground test article design features. This article was designed to the ASAP ground test specifications used for designing the inhouse single fold deployable truss at NASA-MSFC. The test article interfaces the existing NASA air bearing facility for zero-g simulation. It also interfaces the existing base structure. The overall length of the ground test article is about 14 m. There are 10 cells, each about 1.4 m square. The material of construction was specified as aluminum; our design used the 6061-T6 alloy. The drawing shows some of the most significant features of the design. There are four payload stations, each having utility interfaces for both fluid and electrical connections. Six air bearing supports are provided. As indicated on the figure, the test article is oriented on edge for deployment. Subsequent to deployment the test article may be rotated to other positions to allow determination of characteristics in various orientations. Calculations indicate the weight of



HIGHLIGHTS

- Designed to SASP Ground Test Specs
- 10 cells, 46 ft long, 4.6 ft square
- 846 lbs test article weight
- 6061-T6 Aluminum
- Spring deploy, Kevlar cable retract
- Electrical and fluid utilities inside struts
- Interfaces existing facility

FIGURE 18

SUMMARY OF PART 2 BADF GROUND TEST DESIGN the 6061-T6 aluminum structure is approximately 384 kg. Figure 19 shows the stowed configuration and launch packaging for the BADF ground test article.

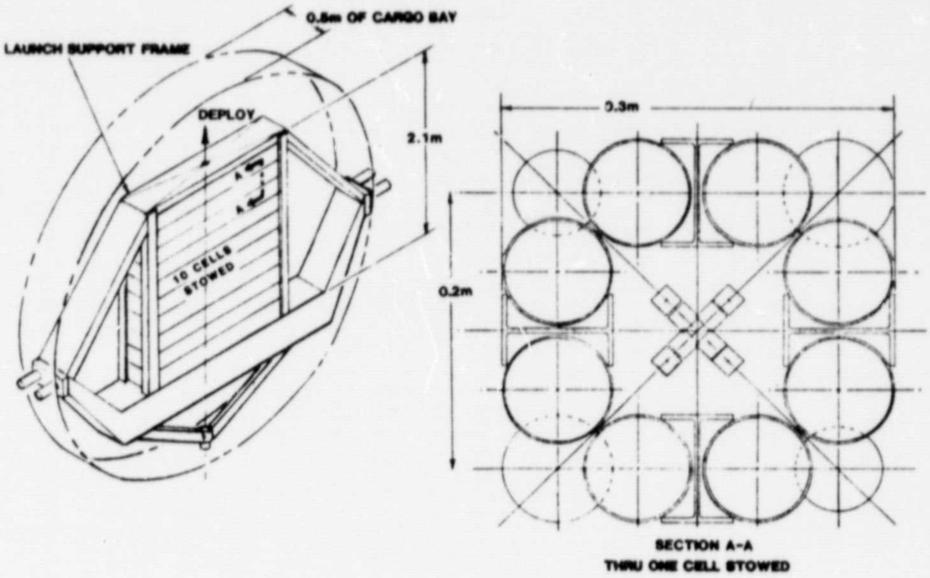


FIGURE 19

STOWED CONFIGURATION & LAUNCH PACKAGING BADF GROUND TEST DESIGN

The article occupies a length of about 0.5 m in the Shuttle cargo bay when packaged with the support structure. The height of the stack of ten stowed cells is about 2.1 m. The cross section through one cell is shown to be approximately 0.2 m x 0.3 m. While it may be unlikely the ground test article constructed from aluminum would be flown in a flight experiment, similar packaging would be obtained with a composite system. Versatility was also provided in the design of the ground test article to allow neutral bouyancy testing by change of the springs in the vertical struts and addition of flotation chambers.

The ground test article design is also suitable for Orbiter flight test experiments with modifications to increase stiffness at partial deployment to accommodate potential Shuttle accelerations up to 0.04 g. The use of localized deployment motors on B nodes to shorten cable runs, beef-up of diagonals, and fabrication of the structure from graphite/epoxy would reduce tip deflections at 70% of deployment by a factor of ten (to 25 cm).

Deployable Volumes

The deployable volume concept evolved during Part 2 for the habitat module is illustrated in Figure 20. The large habitat illustrated in

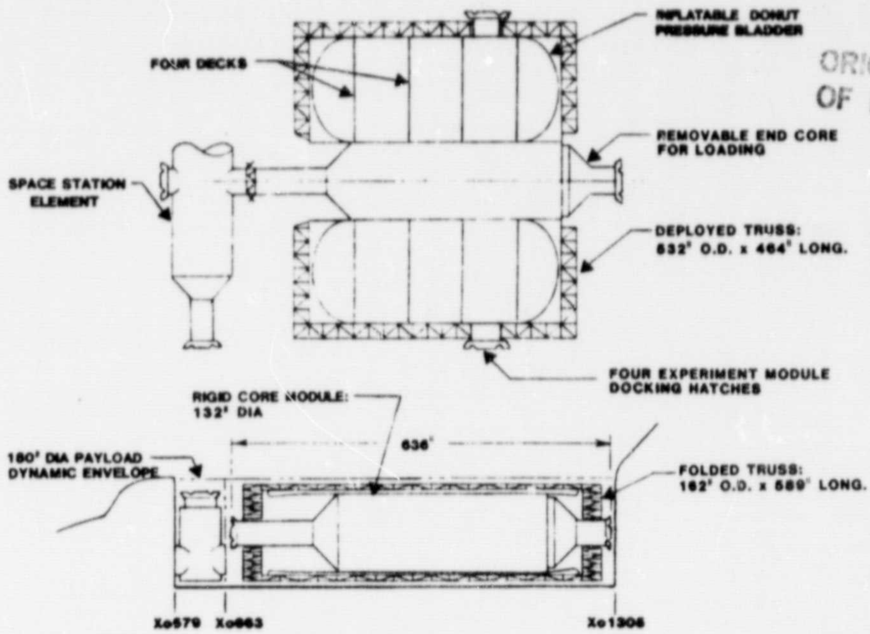


FIGURE 20

HABITAT MODULE STOWED AND DEPLOYED CONFIGURATIONS

the figure was chosen for Part 2 study because it illustrates the capabilities of the deployable volume concept. The module has a volume of about 1130 m^3 (40,000 ft^3) and is sufficiently large to support a 12 man habitat/experiment operation in space. The overall dimensions of the deployed truss structure are a cylinder approximately 13.5m (44.3 ft.) in diameter and 11.8m (38.7 ft.) in length. When stowed the truss folds into a diameter of about 4.1m (13.5 ft.) and a length of about 15m (49.1 ft.). This allows adequate clearance within the 4.57m dynamic envelope of the payload bay for wraping the truss structure with the thermal/meteoroid blanket. The total length of the stowed habitat is about 16.2m (53 ft), leaving space for the Orbiter docking module to be installed to provide both an EVA capability and a docking interface with the Space Station. One principal feature of the configuration is a rigid core module. The core module is delivered to orbit outfitted with essential equipment for crew support and start-up operations. It also provides storage space for other structural elements to allow assembly of the basic structure in the first Shuttle delivery flight. The core module is pressurizable and has a removable aft cone with a 2m square loading hatch, allowing transfer of modularized packaged equipment on subsequent deliveries. Since these packaged articles can be delivered in a pressurized module, the buildup is almost entirely by shirtsleeve operation, and therefore minimizes use of EVA. The modularzation of equipment packaging minimizes installation tasks. The core module also provides a rigid structure for interfacing the Shuttle cargo bay during delivery and for providing a rigid backbone for the deployed volume. The surrounding main volume area is an inflatable pressure bladder, similar to the Part 1 concept except that the bladder is a cylindrical annulus rather than a hollow cylinder. The four decks provide for three levels in the large volume for crew accommodation and mounting of equipment. Four docking hatches are located around the periphery of the deployed volume, and allow interface with experiment modules and with the Shuttle for docking and resupply.

Figure 21 further illustrates buildup characteristics of the deployable habitat module where a pressurized cargo module is shown docked to the aft loading port of the core module. The modularized equipment, transfer pathways, and hatch opening sizes for transfer of equipment in a minimal amount of time are also indicated. The design has been evolved to use the RMS so that no major special equipment is required. The other major results achieved in Part 2 studies are the ability to integrate the deployment of the pressure bladder and the thermal/meteoroid blanket with the truss structure, again minimizing the requirements for EVA.

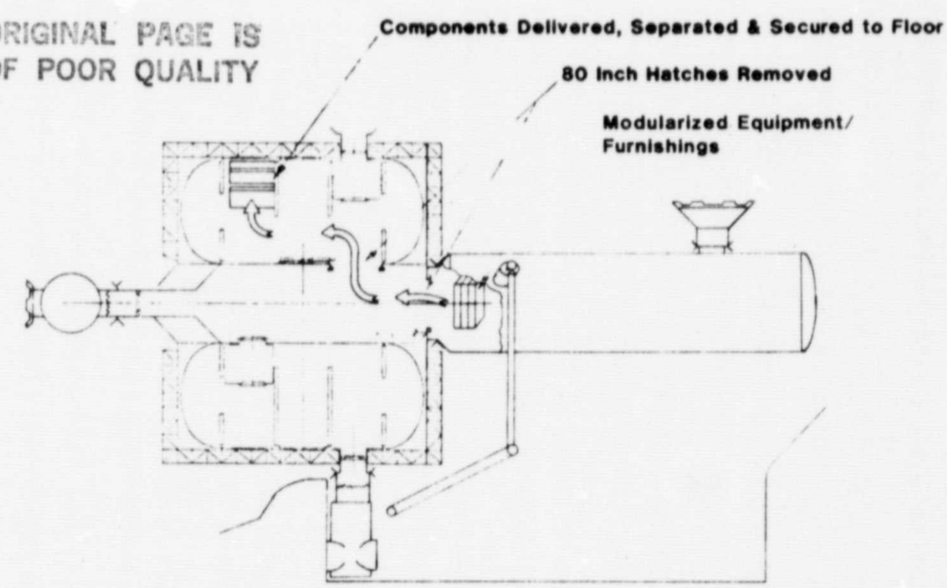


FIGURE 21

SHIRTSLEEVE TRANSFER OF MODULARIZED EQUIPMENT/FURNISHINGS

Figure 22 illustrates the OTV hangar concept developed during Part 2. Similar to the Part 1 results, the hangar opens in a clam shell fashion to accommodate the OTV. The overall dimensions of the hangar truss structure are

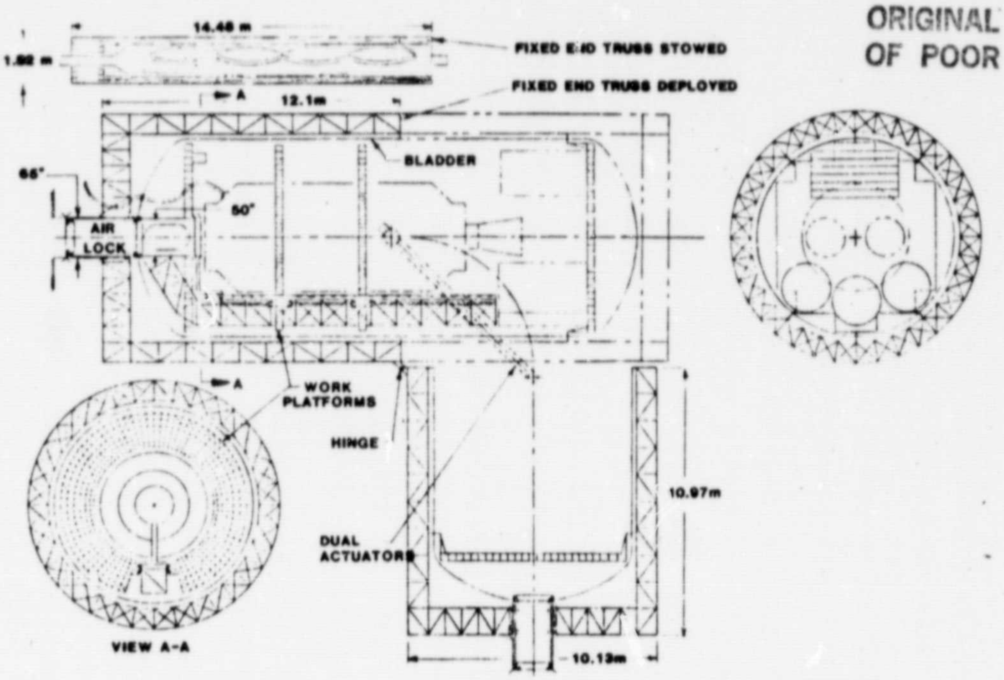


FIGURE 22

OTV HANGAR STOWED & DEPLOYED CONFIGURATIONS

23.1m (75.8 ft) in length by 10.1m (33.2 ft) in diameter. A rigid core is provided in the hangar concept similar to the habitat. The airlock structure, which docks into the Space Station, is connected to a tunnel structure which, in turn, mates an adapter which docks with the OTV. A truss beam, which structurally interfaces the tunnel, provides a support for ingress and egress of the OTV. Moveable work platforms are also supported off the truss beam. The work platform floors are also constructed of deployable structure and stored inside the folded volume. The folded dimensions of the hangar forward truss cylinder are 14.5m (47.5 ft) in length by 1.8m (6.0 ft) in diameter, and thus occupies only a small portion of the cargo bay. The forward section of the clam shell and the hinged aft section of the clam shell are stored in the cargo bay as separate cylinders. The OTV hangar may be operated as a pressurized or unpressurized version. The pressurized version with the bladder installed is illustrated in the figure, showing the bladder interface with the central core structure in the airlock area. Each bladder half is provided with a support ring and seal at the clamshell opening on the forward and aft sections. The folded configuration of the seal ring is shown stored on the inside of the folded truss structure. The OTV configuration sketched in the figure is representative of a projected version of a reuseable OTV, and is one of the larger sizes expected to be used with the hangar. In the aft portion of the clam shell storage space is provided for such items as spare ballutes or engines. A platform for storage is also indicated. A second airlock is installed in the aft clam shell, which is necessary for an alternate egress path when the hangar is used in its pressurized version. Similar to the deployable habitat, the deployable hangar has the bladder and the external thermal/meteoroid insulation blankets preattached. These deploy with the structure. However, subsequent to deployment, RMS operation is necessary to install the airlocks on both the forward and aft ends. A combination of RMS and EVA operation is also required to unfold and install the bladder seal ring structure. The launch storage concept in the Shuttle cargo bay makes use of a core canister internal to cylindrical truss structure, similar to that used with the deployble habitat. The canister diameter is approximately 1.3m. Part of its structure is the docking tunnel, and this diameter is continued through the entire length of the truss. End plates are provided to support the canister during launch, providing a rigid backbone for launch loads. Stored inside the canister are the folded work platforms illustrated by the small circle inside the canister in the figure, and the folded rail support beams. A rigid docking ring guide is also stored inside the canister. It should be possible to deliver and erect the hangar in a single Shuttle flight.

The BADF truss structure was found to provide the best overall compatibility with both deployable volumes, and permits integral attachment and deployment of the external thermal/meteoroid blanket and the pressure bladder. Excellent micrometeoroid and debris protection is inherently provided by the blanket/truss/bladder configuration, resulting in a 10-year probability of no habitat meteoroid penetration of 0.998 for meteoroids and 0.95 to 0.975 for debris (1978 model), depending on whether radiators are added to the outside diameter. Shielding from space radiation is adequate for low inclination LEO missions for 180-day crew rotation; additional shielding can be added as required.

2.0 GROUND TEST ARTICLE DESIGN

This section presents design requirements, discusses major design features, and summarizes supporting analyses for the ground test article. Also inclosed in this section are reduced copies of the design drawings.

2.1 DESIGN REQUIREMENTS

Figure 23 illustrates the ground test article physical shape and dimenions and interface requirements. Table 2 is a summary of the detail

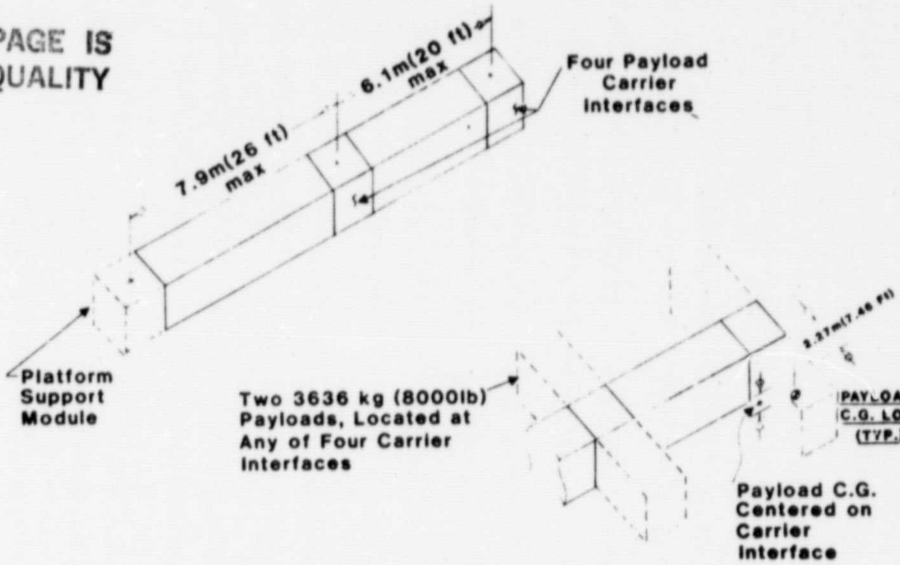


FIGURE 23

GROUND TEST ARTICLE DIMENSIONAL AND INTERFACE REQUIREMENTS

requirements for the ground test article design. These were extracted from Reference 7, which is the specification for the NASA inhouse Single Fold ground test article design of a representative SASP arm. Based on these requirements a definition of the utilities bundles for installation in the structure was derived and is presented in Figure 24, which also includes a summary of the weight of the utility bundles.

2.2 DESCRIPTION OF DESIGN

A series of 11 layout drawings were defined to describe the ground test article layout design in sufficient detail. These are listed in Table 3 and may be used as a guide to the drawings which are contained in Figures 25 through 35. Figure 25 is also in the nature of a guide in that it is a

TABLE 2

SUMMARY OF GROUND TEST ARTICLE REQUIREMENTS

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Launch Packaging

- Orbiter Cargo Bay, 4.3m (14 Ft) Dia Envelope

Misalignment and Distortion

- Measured between carrier interface and platform arm-to-support module interface
- Max ± 1.0° due to fab tolerances, joint deadband, thermal distortion, interface misalignment
- Max ± 0.1° dynamic instability due to cyclic thermal distortion, environmental and induced loads, and deadband

Structural Strength

- Withstand 0.04 g's deployed with two 3636 kg (8000 lb) payloads due to maneuver and reboost
- Test article withstand 1-g horizontal ground deployment or simulated 0-g, without payloads
- Adequate for application of static and dynamic ground test force application, horizontal or vertical (for measure static defl., load dist., vibration characteristics)
- Withstand launch load and vibration environment in compacted form
- Withstand impact loads resulting from payload installation/removal and Orbiter berthing

Structural Stiffness

- First mode structural frequency > 0.01 Hz, arm deployed with two 3636 kg (8000 lb) payloads

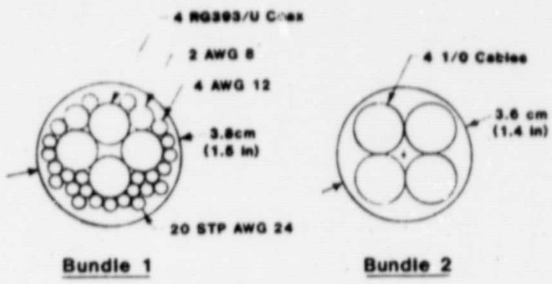
Payload Mechanical Interface

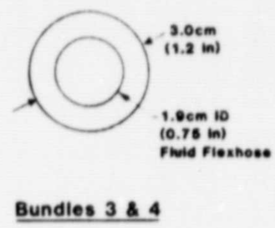
- Orbiter RMS installation and removal of payload carrier
- EVA backup role only
- Automatic latching and initiation of disengagement including utility connectors (flight article)
- ESA pallet nominal as payload carrier, modified to contain carrier portion of interface

Payload Utilities Accommodation

- Separate electrical harness and fluid lines to each of four payload interfaces
- Electrical harness: 4 each 1/0; 2 each 8 AWG; 4 each 12 AWG; 20 each TSP AWG 24; 4 each RG393/U Coax
- Fluid lines: 2 each 1.9 cm (0.75 inch) I.D. lines

Ref: NASA-MSFC Memo EP-13(80-14), 25 Feb. 1980





Utilities Wet Weight

Bundle No.	Kg/m	(Lb/Ft)
1	1.78	(1.19)
2	2.56	(1.72)
3	0.95	(0.64)
4	0.95	(0.64)
Total	6.25	(4.19)

FIGURE 24

DEFINITION OF UTILITIES BUNDLES

TABLE 3

221-60182 LAYOUT DRAWING LIST BADF GROUND TEST DESIGN

Sht	Title	Description
1	Assy and Interfaces Layout	Isometric Assy & Guide to Detail L/O shts
2	Longitudinal/Lateral Layout	Tube with lugs and cover over slot
3	A Node Layout	Fitting with lugs, sheave bkts, bending deploy springs and cover
4	B Node Layout	Fitting with lugs and cover
5	Vertical Telescope Layout	Double telescope joints with locks and linear deploy spring
6	Side & Surface Diagonal Layout	Side & BHD Diag I-beams with air brg bkts & sheaves. Surf diag with fold initiate cams
7	Cable Reel Layout	Cable reel design with level wind fair leads and gear motor drive
8	Cable Routing Diagram	Cable routing isometric
9	Payload Interface Layout	Coupler interface dimensions on 55 node centerline. Utility connectors locations
10	Base Str Interface Layout	Attachments to base facility
11	Utilities Instl Thru Nodes	Isometric of A and B node exploded view

pictorial illustration of the application of various detail layout drawings to different elements of the truss. Figure 35, showing the utilities installation through the nodes, is also helpful in seeing the overall design approach. It shows in an exploded view how the deploy-initiate springs are integrated into the longitudinal and lateral struts at the node pivots, and how they encircle and provide protection for the utilities bundles which are passed through the center of these coil springs.

Figure 26 provides detail information on the lateral and longitudinal strut design. These struts are fabricated from standard aluminum tubing. A screwed on cover is provided for installation of the utilities in the assembled structure. Dual pivot lugs are welded into the ends of the struts. The materials selection is 6061-T6 aluminum which is the same weldable material used on all elements of the aluminum structure. Figure 27 provides detail on the A node design. The A node is fabricated from welded plates. Also shown in the layout is a cable sheave installation and installation of the pins at the dual pivot lugs. Because press fit roll pins are used there is no free motion in the pivots. If high production were required the nodes could be made from castings to minimize fabrication costs. Figure 28 shows similar information for the B node. Both A and B nodes have screwed-on covers to provide for installation of the utilities as a complete harness in the assembled structure. Figure 29 presents detailed information on the telescoping vertical strut. This strut employs three concentric standard gage aluminum tubes. An Elgiloy compression spring is contained down the center of the strut to provide deployment energy. A latch release mechanism is also detailed on the figure. As indicated on the drawing the Aramid (Kevlar 29) refold-deploy control cable is terminated in a spring clamp to control post-tension. Small Teflon balls are installed in holes drilled into aluminum sleeves located between the concentric tube to provide friction-free operation and to avoid motion due to the small clearances. Figure 30 provides information on the diagonal struts which are standard AND 10140-3002 I-beam extrusions for the bulkhead and side diagonals. The surface diagonals are solid square aluminum rods. Also indicated are the bulkhead diagonal base ends showing their position relative to the A nodes, and also showing the installation of the air bearing supports.

The installation of the cable reel with a representative gear box and coupling design is shown in Figure 31. It is on the blukhead diagonal at the truss base, and winds all the cables on one reel. A level-wind mechanism is included to insure reliable and repeatable winding of the cables. A torque arm on the threaded reel spindle is adjusted to stop the reel when the proper cable travel is obtained for both deploy and refold. In Figure 32 an isometric drawing shows the cable routing diagram. Notes on that drawing provide detail information on rigging the cables. A total of 31 cables are used which are routed down one side of the truss through the reel hub slot and back up the other side. The 0.86 mm diameter Kevlar 29 cables have a 90 kg breaking strength. This 90 kg is well in excess of the 27 kg maximum which is applied in post-tensioning the cables. A slip clamp has been designed and a feasibility test run to show that the 27 kg maximum can be controlled in this fashion.

Figure 33 shows the payload interface layout. Autolock couplers are used on each of the four interfacing nodes at a payload station. Utility connectors are also illustrated on the diagram. The installation procedure is that first the mechanical coupling is completed, then a special device with an electrical pull in screw mates the utility connectors. Such a device was conceptually designed during Part 1 and presented in Ref. (3). For ground test this could be carried out manually to avoid development costs for the device at this time. Figure 34 shows the revisions to the NASA-MSFC base structure required to interface the BADF ground test article. These revisions are minor and require adding two load cells as well as some other detail changes illustrated on the drawing. Table 4 presents the weight summary of a BADF ground test article. Each item is first listed and are then summed to

TABLE 4

WEIGHT SUMMARY BADF GROUND TEST DESIGN

Item	Weight/Item (Lbs)	Weight/Cell (Lbs)	Weight/BHD (Lbs)
A Node	3.2	6.4	6.4
B Node	1.0	2.0	2.0
Side Diag	6.2	12.4	
Surf Diag	3.0	12.0	
Vertical	2.2	4.4	4.4
Longitudinal	2.8	11.2	
Lateral	2.8	5.6	5.6
Bending Springs (Ends of Vert)	2.0	4.0	4.0
Compression Springs:			
Up Going	2.1	2.1	2.1
Down Going	2.3	2.3	2.3
Utilities All 4 Long	4.25/Ft	19.5	
TOTALS		81.9	26.8

10 Cell Truss:
(10) 81.9 + 26.8 = $\boxed{845.8 \text{ Lbs}}$

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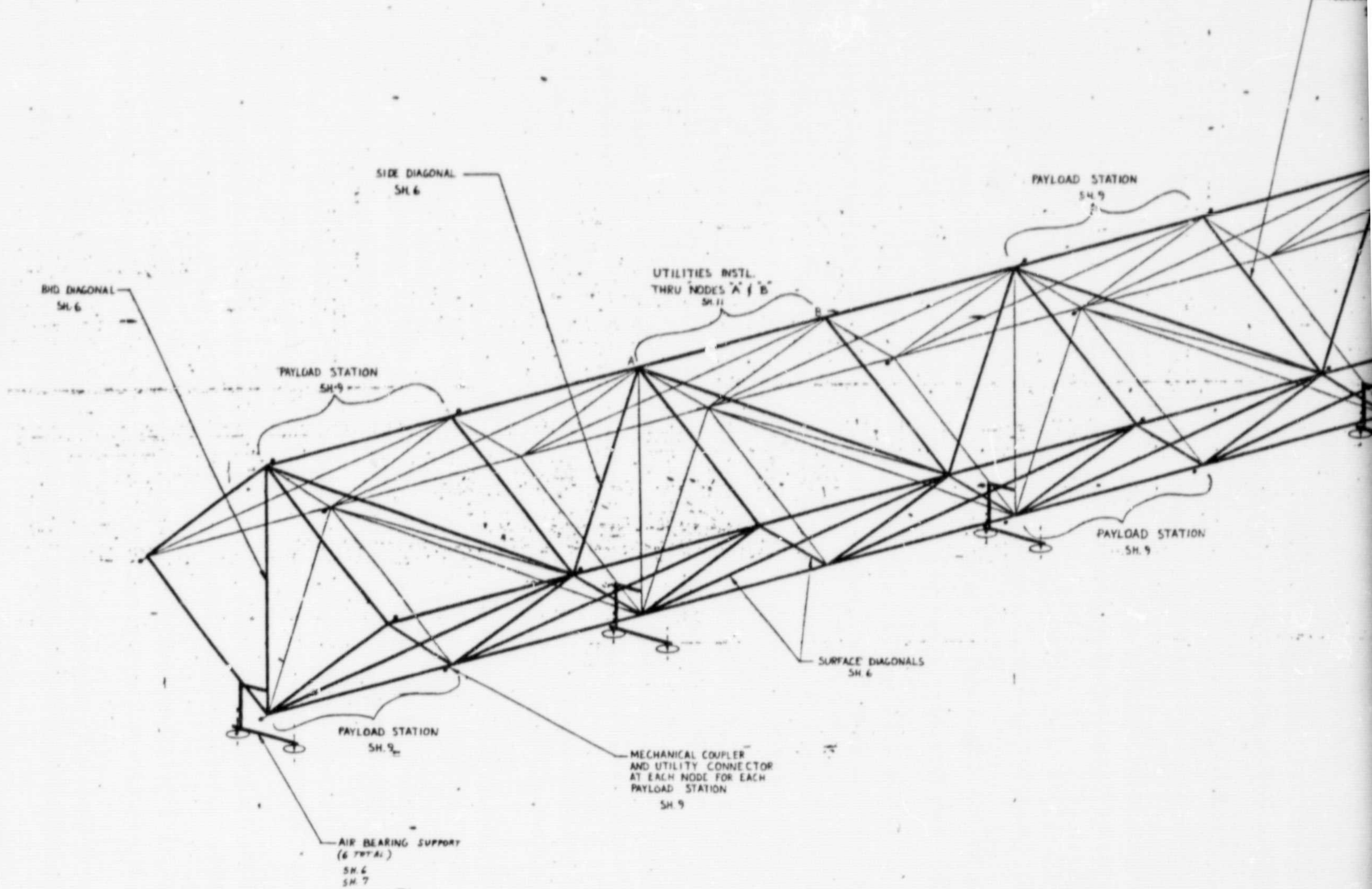

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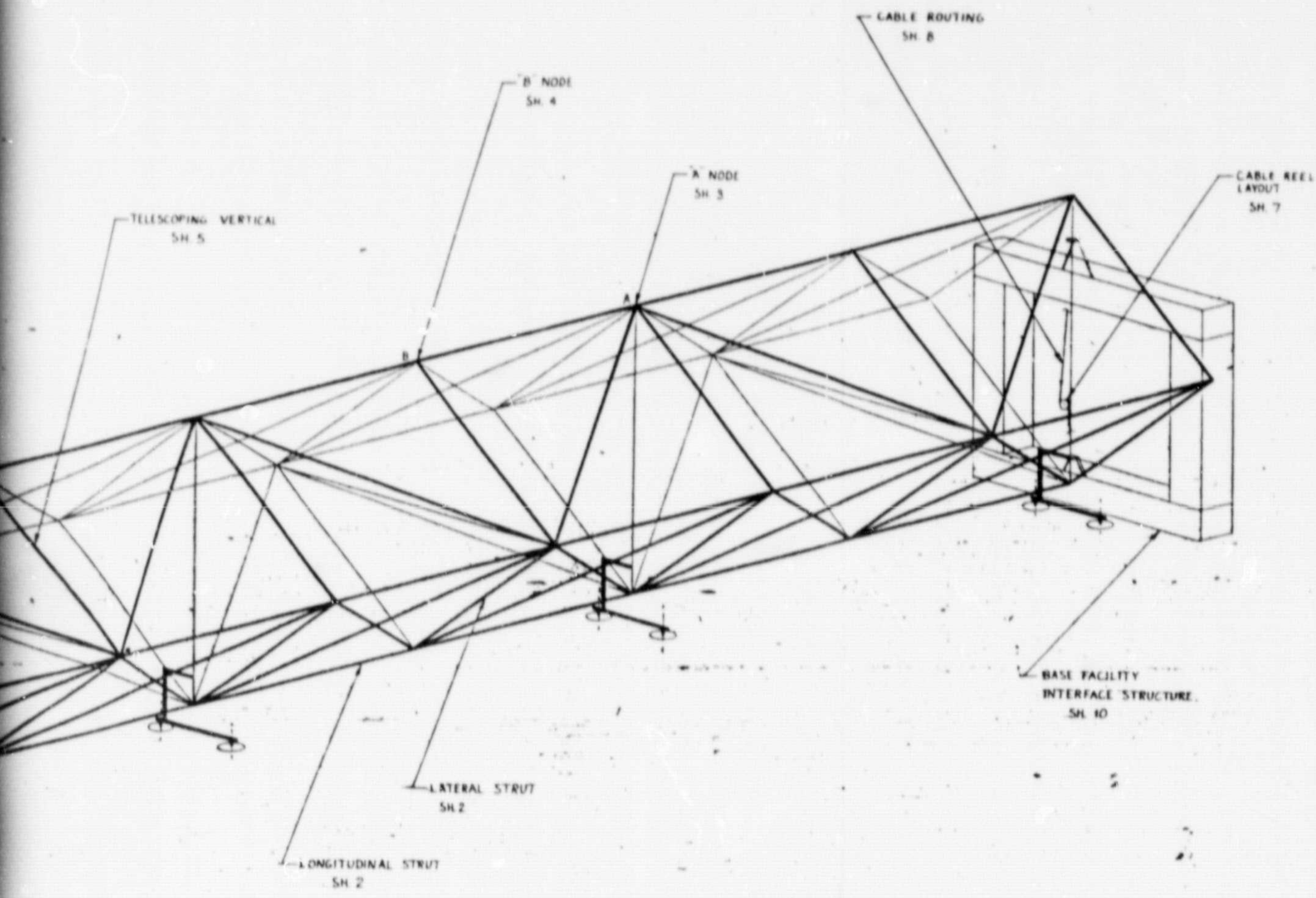

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FIGURE 25

VOUGHT CORPORATION

ASSY AND GUIDE TO LAYOUTS
BADF GROUND TEST DESIGN
-SASP DEPLOYABLE TRUSS

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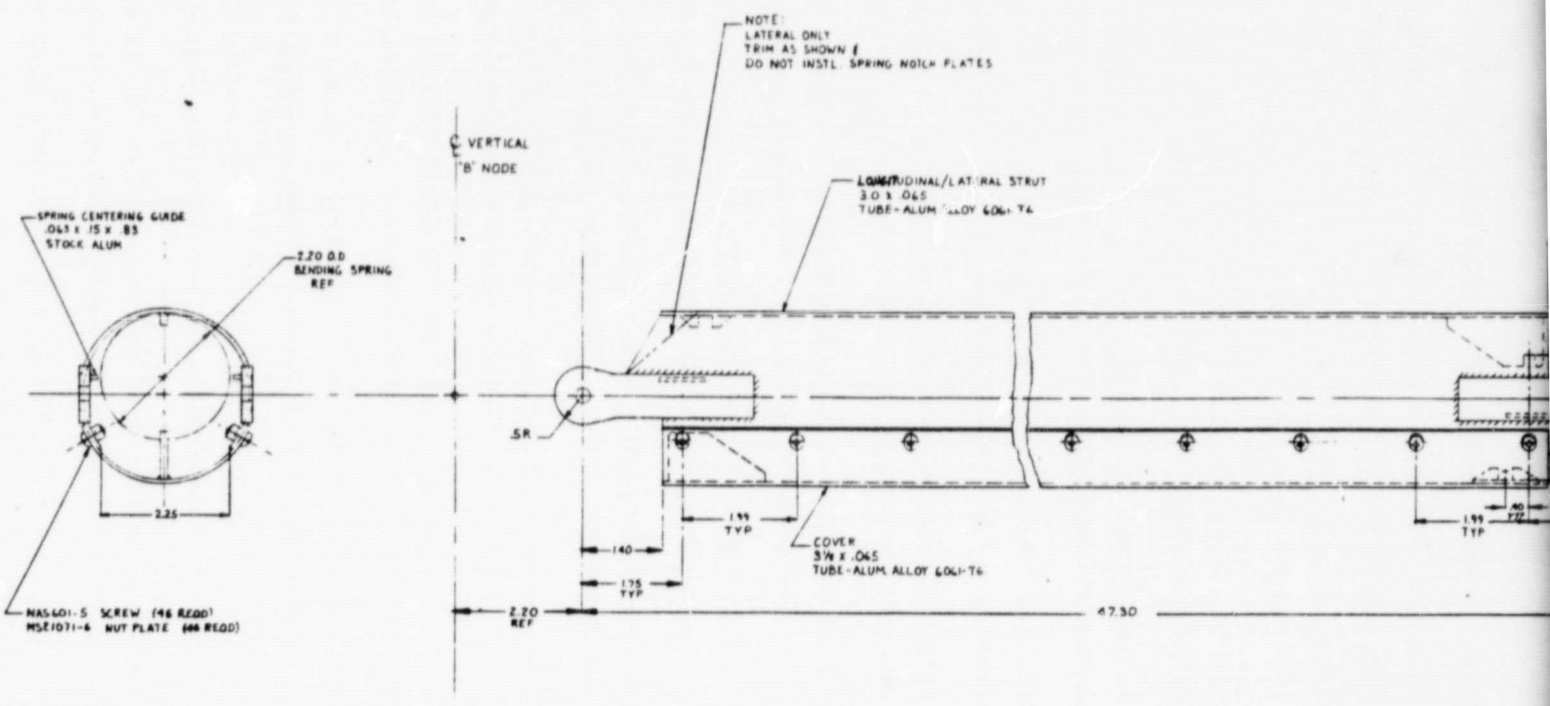

FOLDOUT FRAME

NOTES:

1. ALL WELDED MATERIAL 6061-T6
2. USE HEAT SINK CLAMPS ON ALL CLEVIS LUGS DURING WELDING TO MAINTAIN HIGH LUG STRENGTH

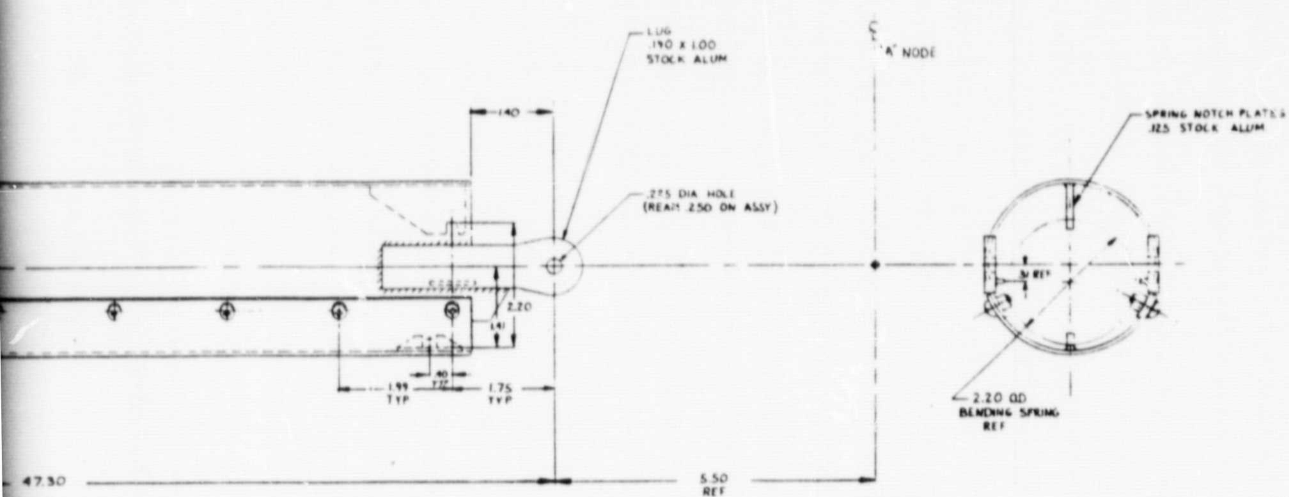

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FIGURE 26

VOUGHT CORPORATION

LONGITUDINAL/LATERAL STRUT LAYOUT
BALF GROUND TEST DESIGN
– BASE DEPLOYABLE TRUSS

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SHEET 2

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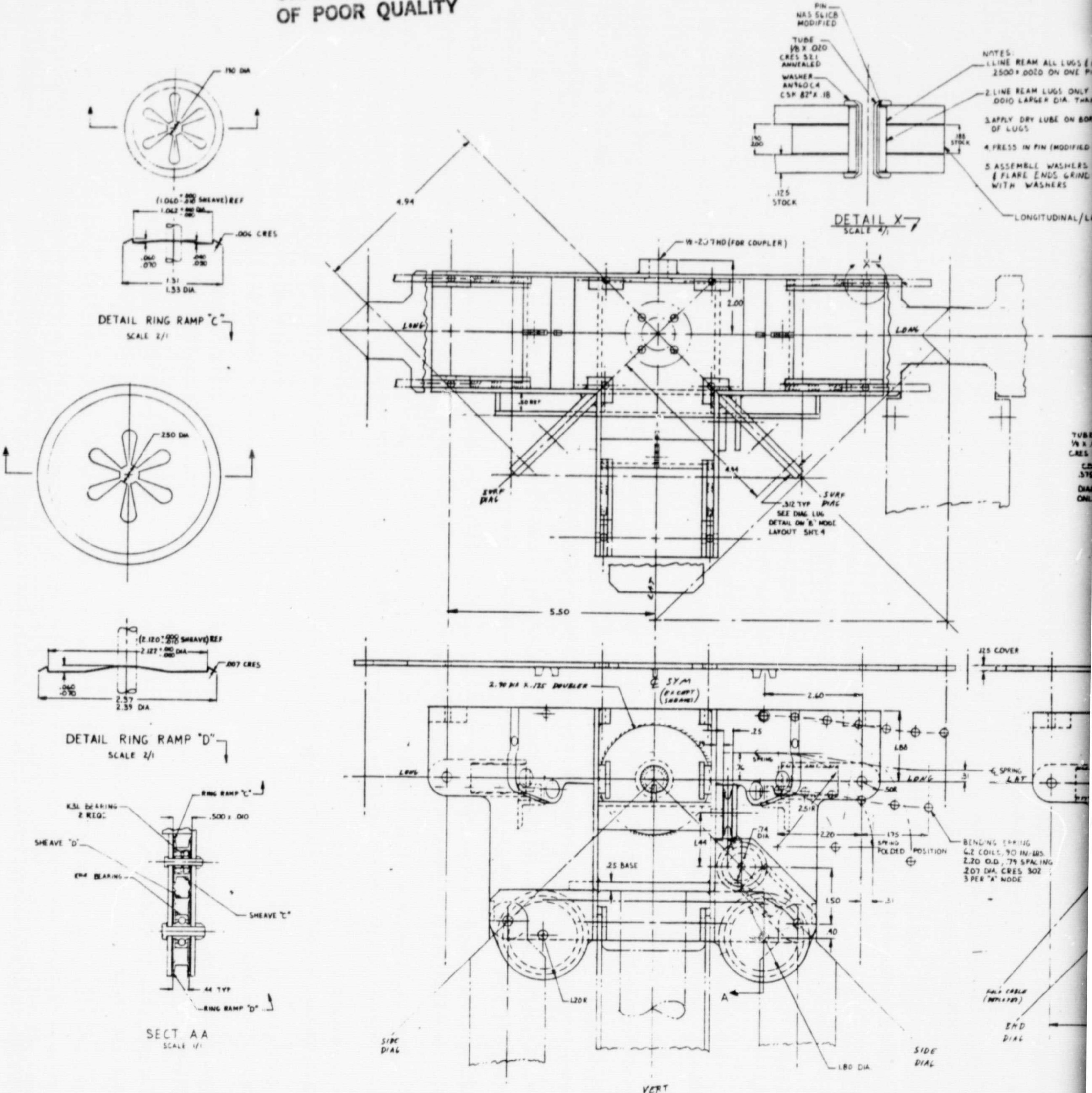

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NOTES:

1. ALL WELDED MATERIAL 6061-T6
2. USE HEAT SINK CLAMPS ON ALL CLEVIS LUGS DURING WELDING TO MAINTAIN LUG STRENGTH.

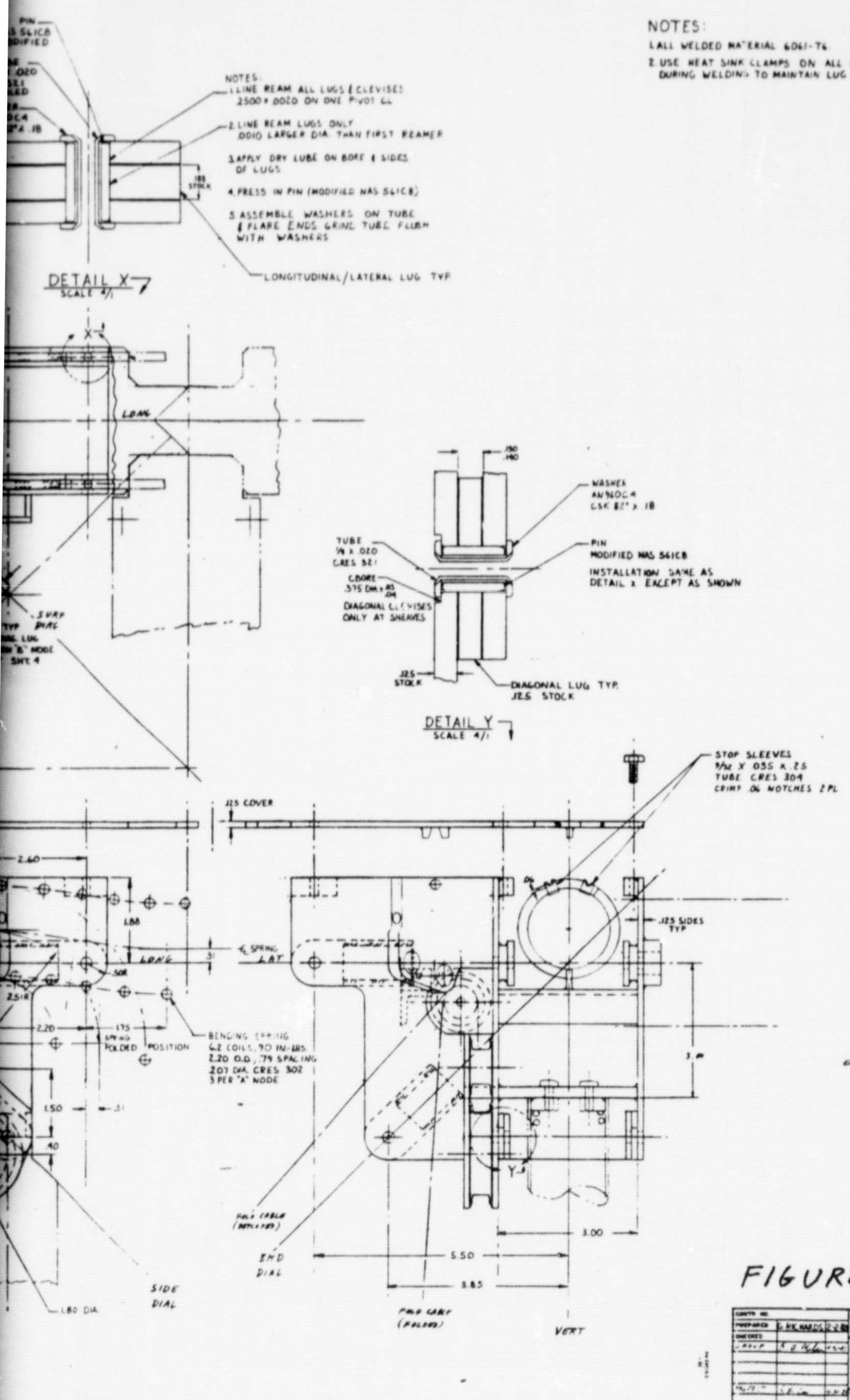

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FIGURE 27

VOUGHT CORPORATION

"A" NODE LAYOUT - BADF GROUND TEST DESIGN - SASP DEPLOYABLE TRUSS

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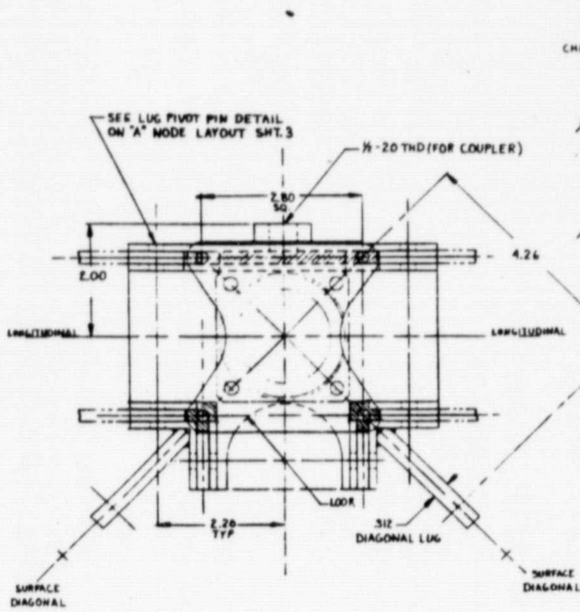
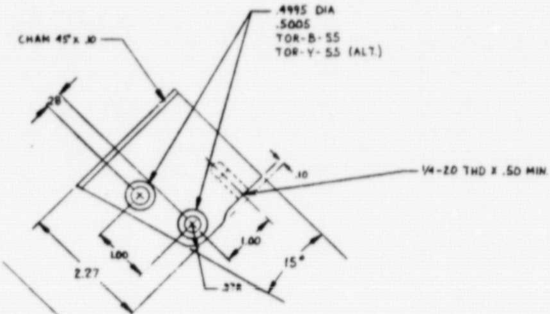
SCALE 1/1

NOTES:

1. ALL WELDED MATERIAL 6061

2. USE HEAT SINK CLAMPS ON DURING WELDING TO MAINT





DETAIL DIAGONAL LUG
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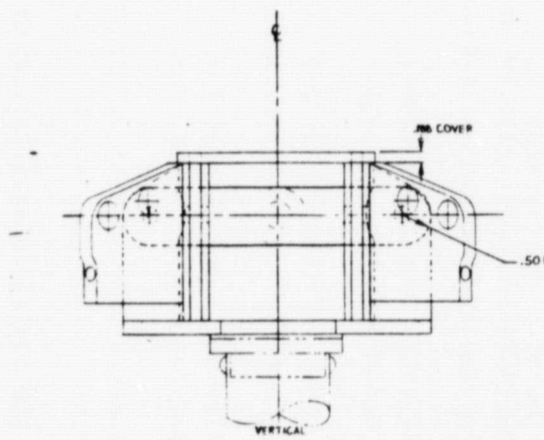

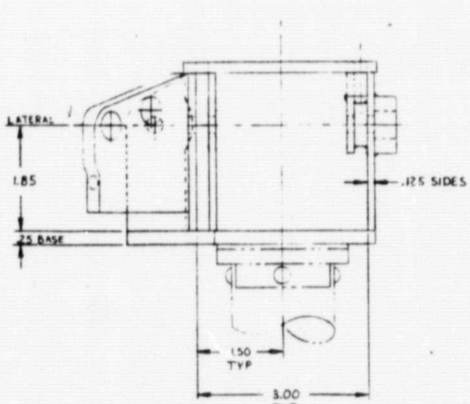

FOLDOUT FRAME

NOTES:

1. ALL WELDED MATERIAL 6061-T6
2. USE HEAT SINK CLAMPS ON ALL CLEVIS LUGS DURING WELDING TO MAINTAIN HIGH LUG STRENGTH

2 FOLDOUT FRAME

FIGURE 28

VOUGHT CORPORATION

"B" NODE LAYOUT-
BADF GROUND TEST DESIGN
[illegible]

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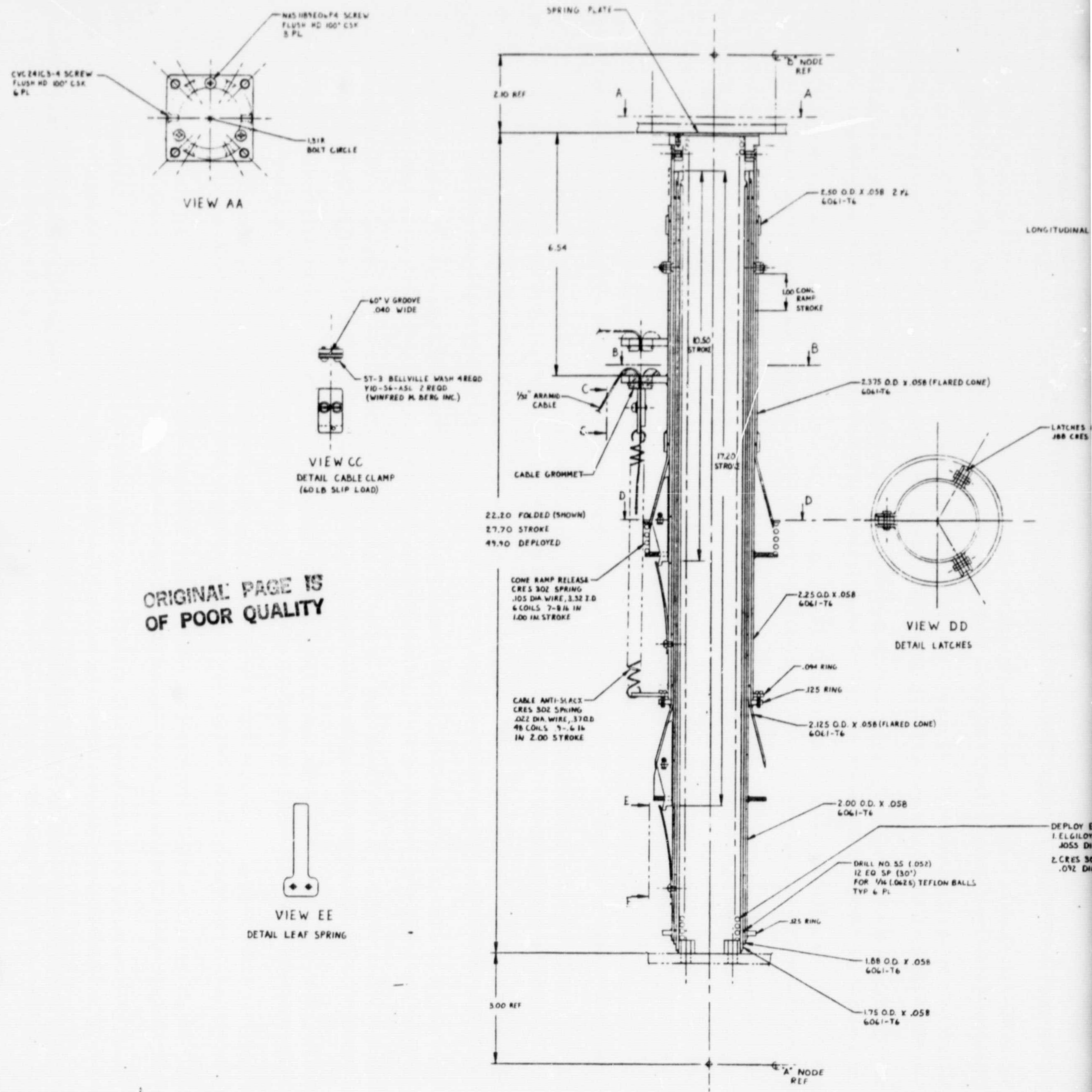

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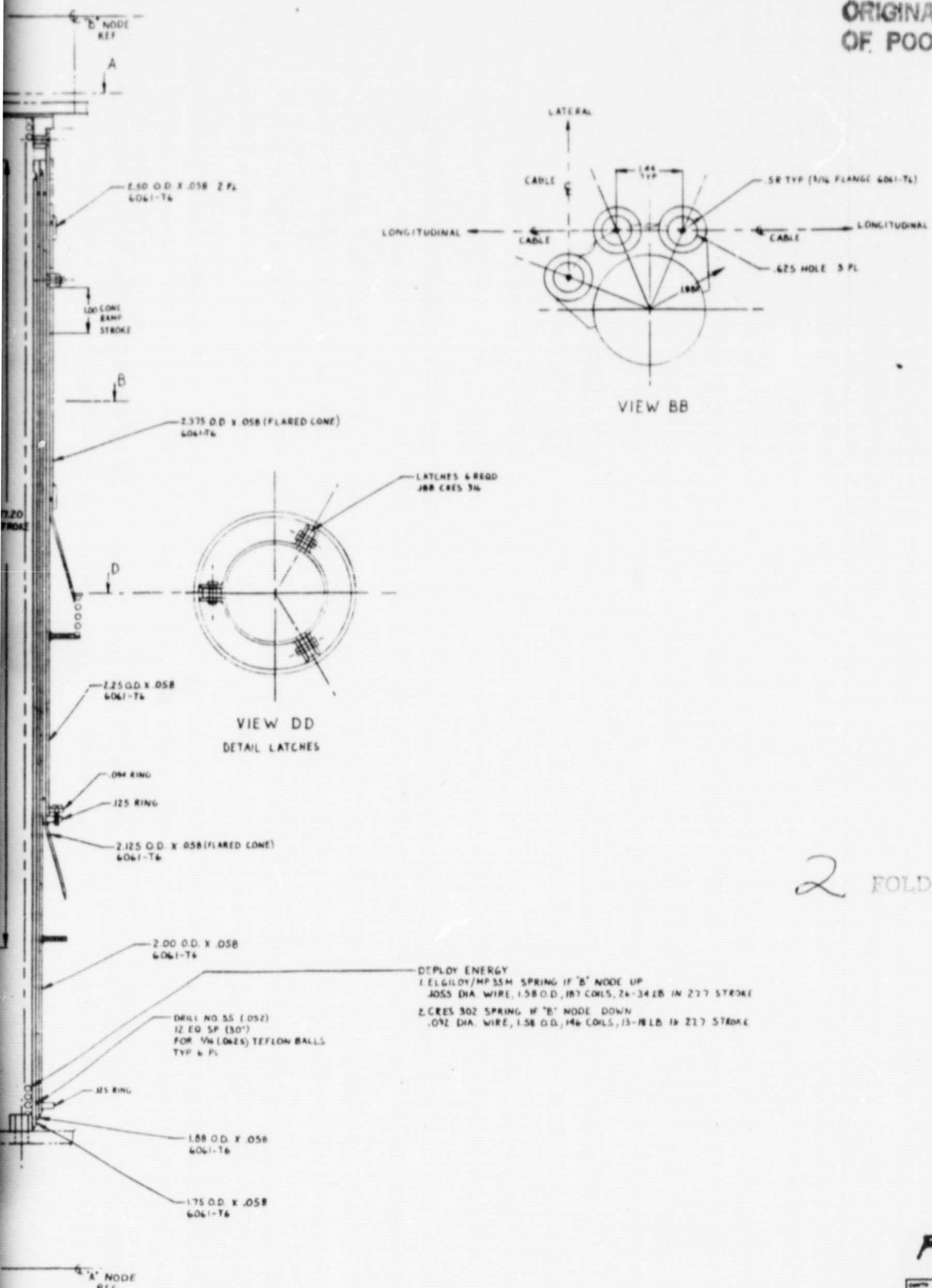

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FIGURE 29

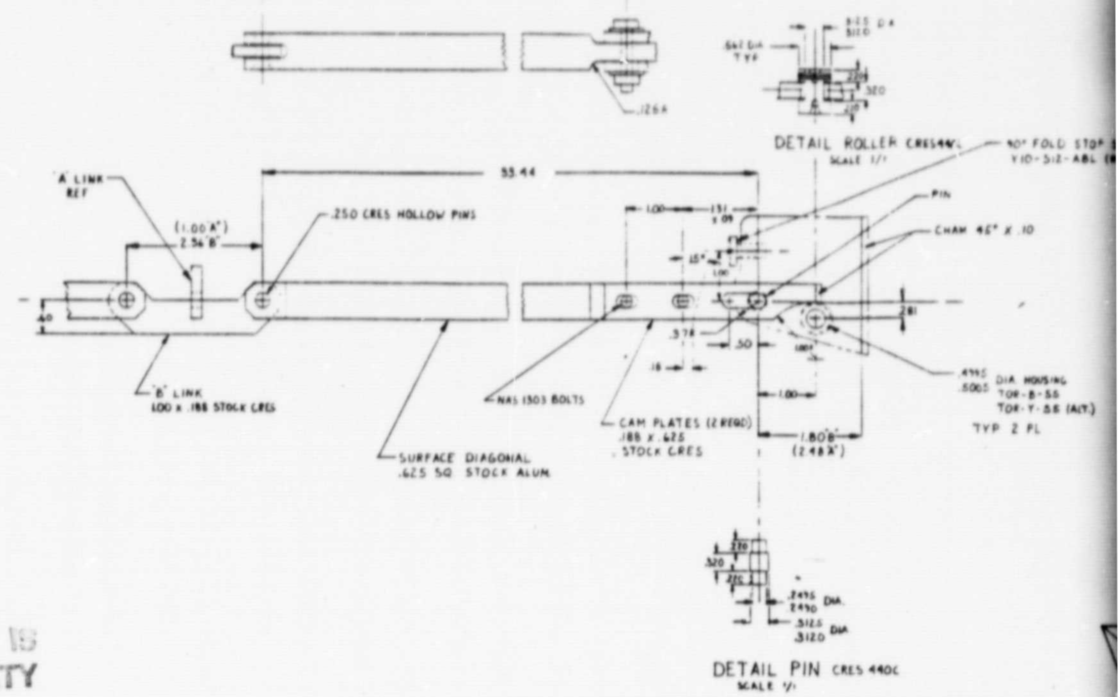
VOUGHT CORPORATION

TELESCOPING VERTICAL STRUT
BADF GROUND TEST DESIGN
-SASP DEPLOYABLE TRUSS

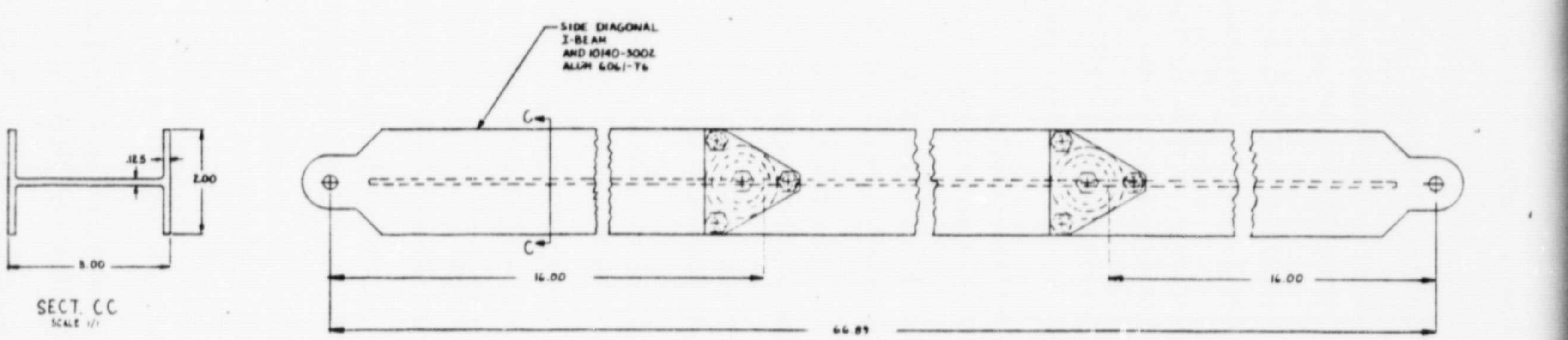
PREPARED G. RICHARDS

80378 221-60182

SCALE 1/1



AIR BEARING SUPPORT



THIS END TOWARD
CABLE REEL AT BASE

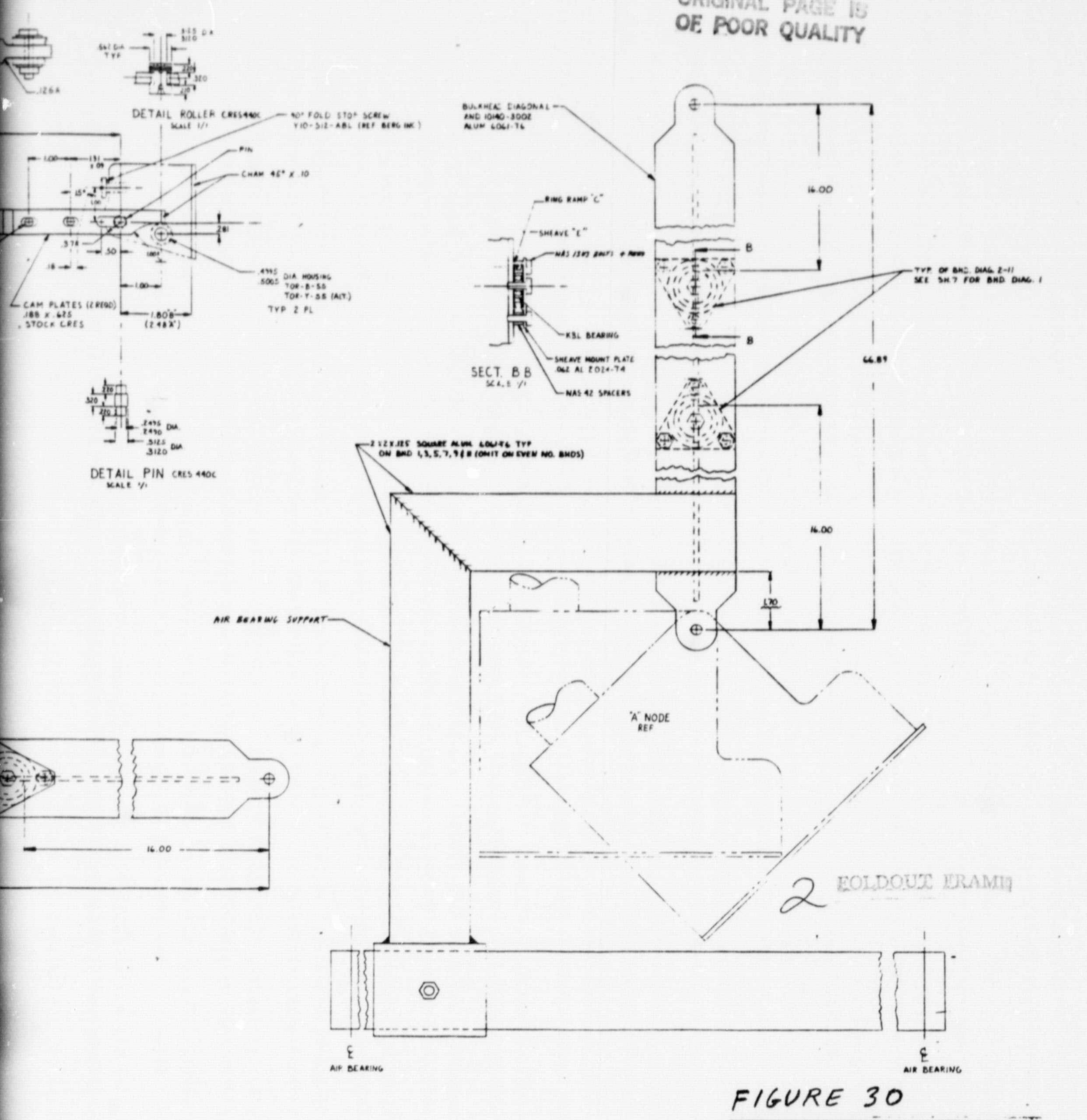
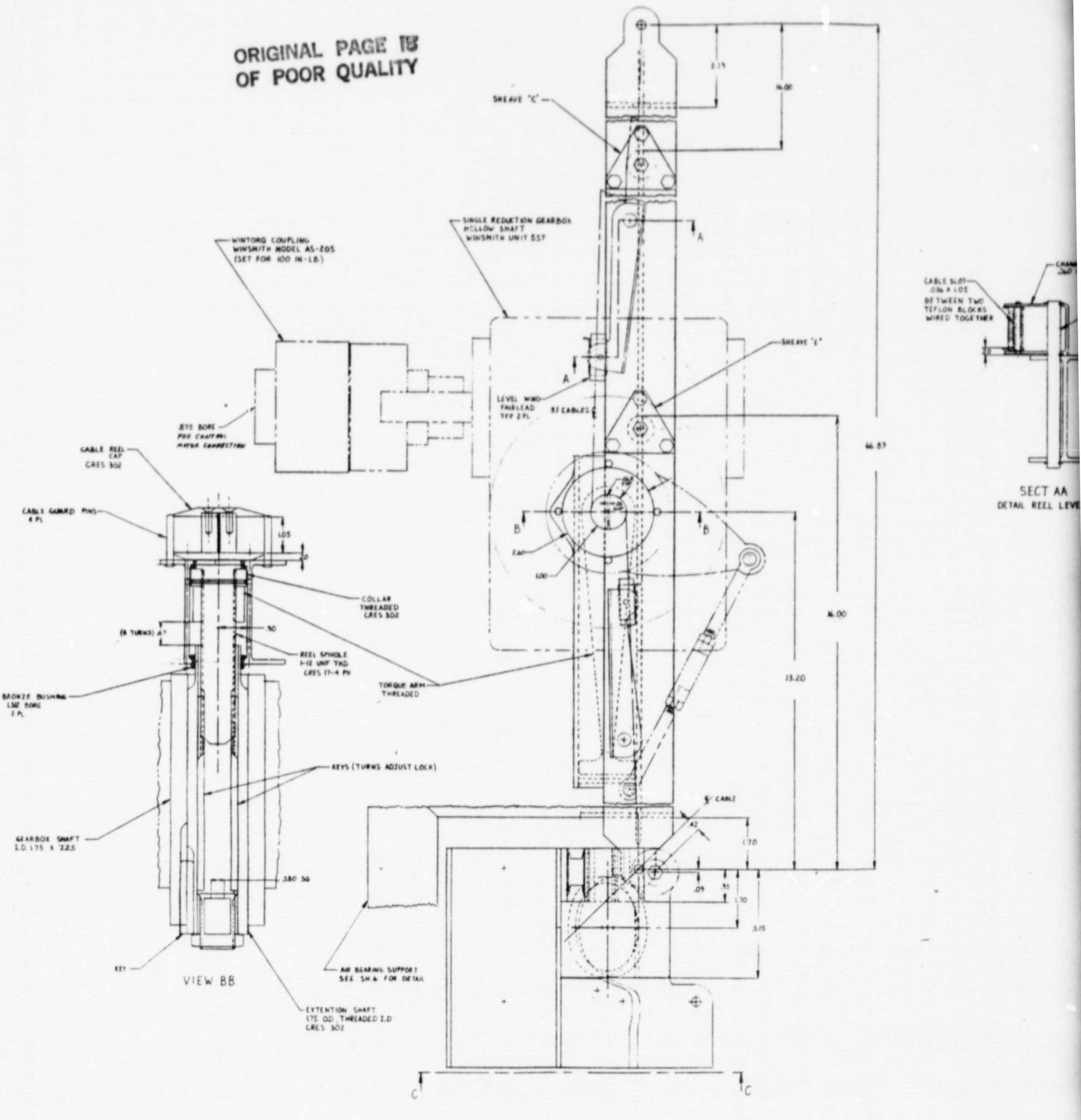


FIGURE 30

VOUGHT CORPORATION	
SURFACE, SIDE & BULKHEAD DIAGONALS LAYOUT BADF GROUND TEST DESIGN - SASP DEPLOYABLE TRUSS	
80378	221-60182



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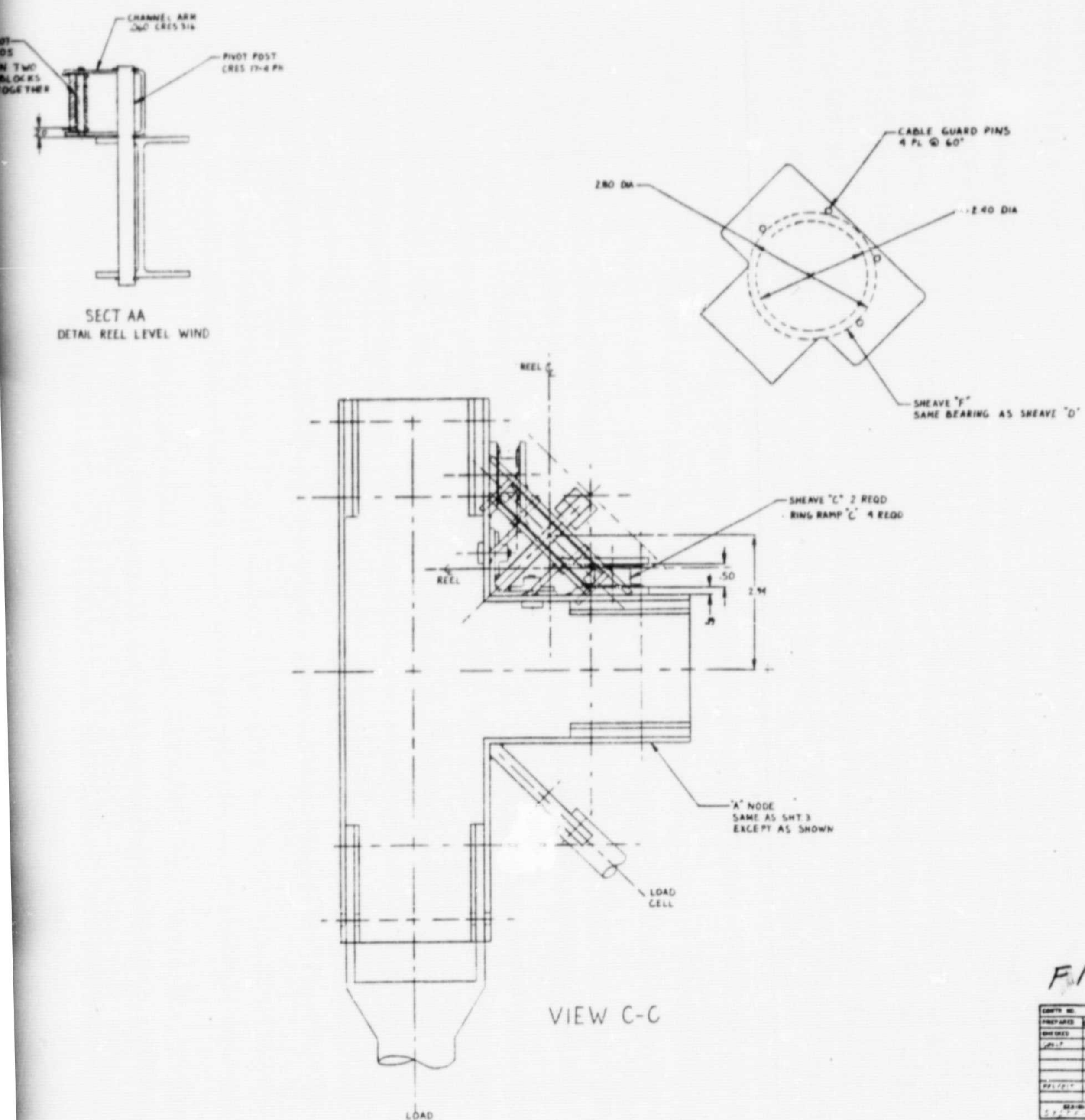

FIGURE 31

VOUGHT CORPORATION

CABLE REEL LAYOUT
BADF GROUND TEST DESIGN
-SASP DEPLOYABLE TRUSS

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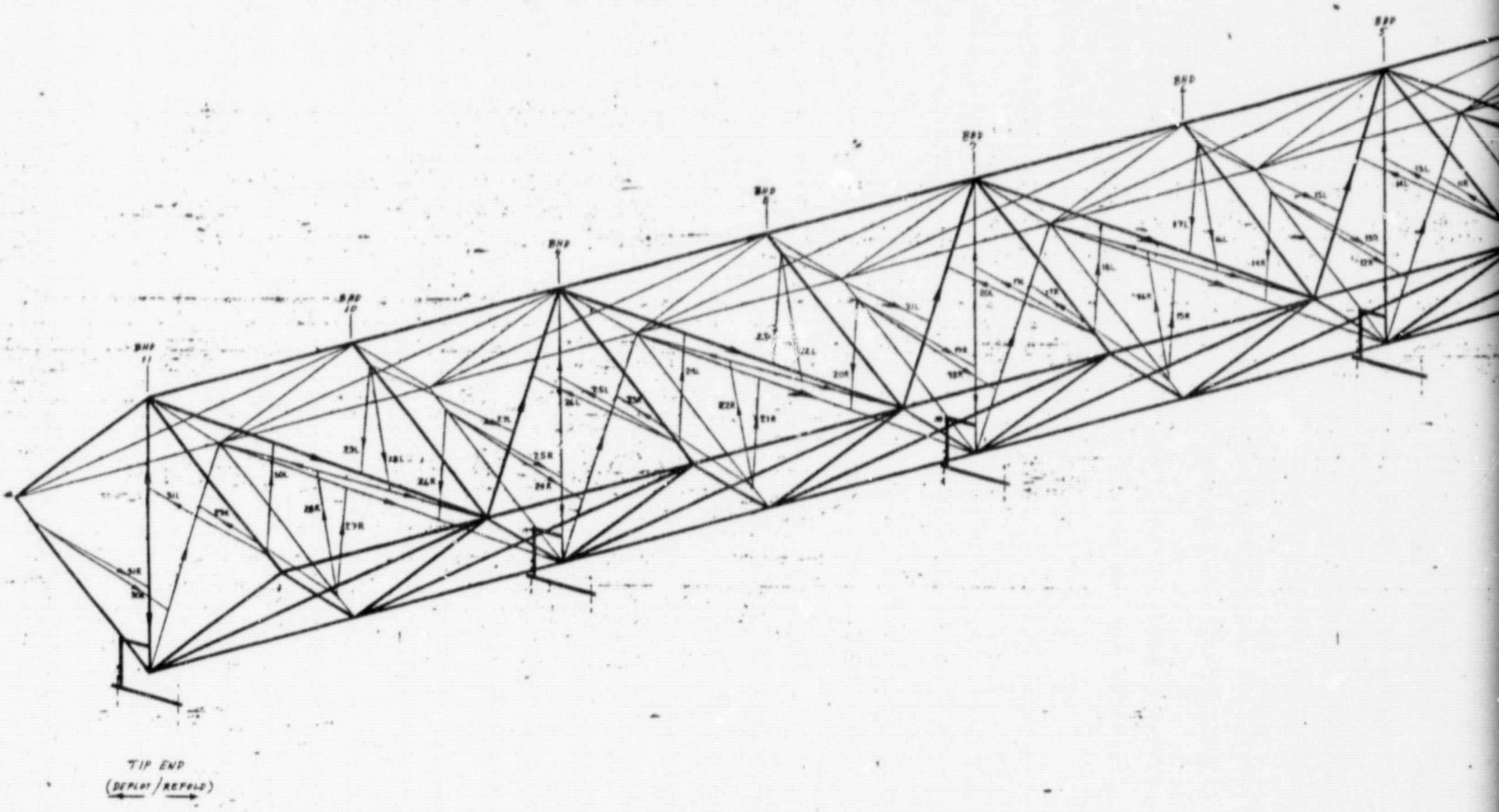

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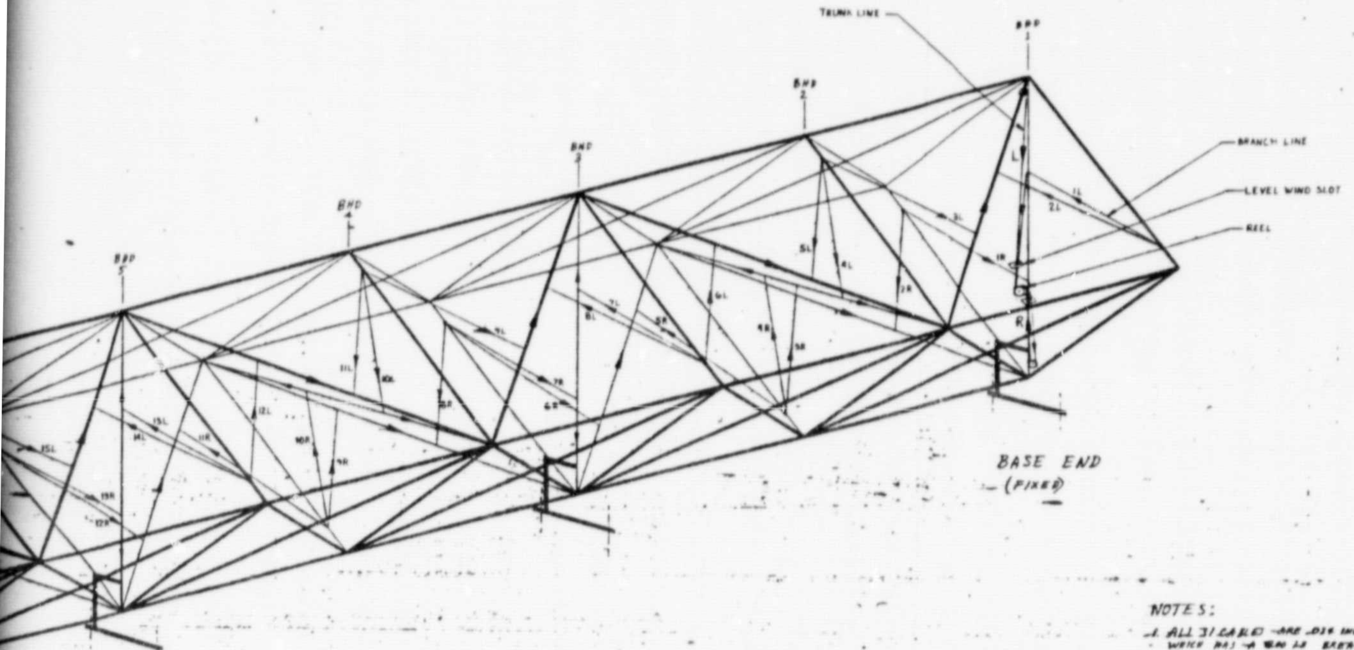

NOTES:

1. ALL 31 CABLES ARE [illegible] INCH DIA TWISTED ARAMID (KEVLAR 29) WHICH HAS A [illegible] BREAKING STRENGTH.
2. [illegible]
3. ALL 31 CABLES [illegible] IN PARALLEL THROUGH THE SLOTTED [illegible] AS SHOWN ON SHT 9.
4. [illegible] ALL 31 CABLES ARE [illegible] IN PARALLEL [illegible] A LEVEL WIND ON THE REEL.
5. [illegible] ALL 31 CABLES [illegible]
6. AN ADDITIONAL [illegible] OF ALL CABLES [illegible] SLIP CLAMP SHOWN ON SHT 5.
7. REEL WINDING IS THEN STOPPED WHEN THE [illegible] ARM ON THE REEL [illegible] (SEE SHT 9)
8. THE [illegible] ARM WILL STALL THE REEL AND [illegible]
9. WHEN THE REEL IS FULLY [illegible] THE TRUSS, THE [illegible] ARM WILL [illegible] AND STALL THE REEL AND [illegible].
10. AT THIS POSITION THE CABLES [illegible] WILL BE REMOVED BY THE ANTI-SLACK SPRINGS [illegible] ON THE CABLE CLAMP.

2 FOLDOUT FRAME

FIGURE 32

VOUGHT CORPORATION	
REFOLD-DEPLOY CONTROL CABLE ROUTING DIAGRAM, BADF GROUND TEST DESIGN - SASP DEPLOYABLE TRUSS	
80378	221-60182

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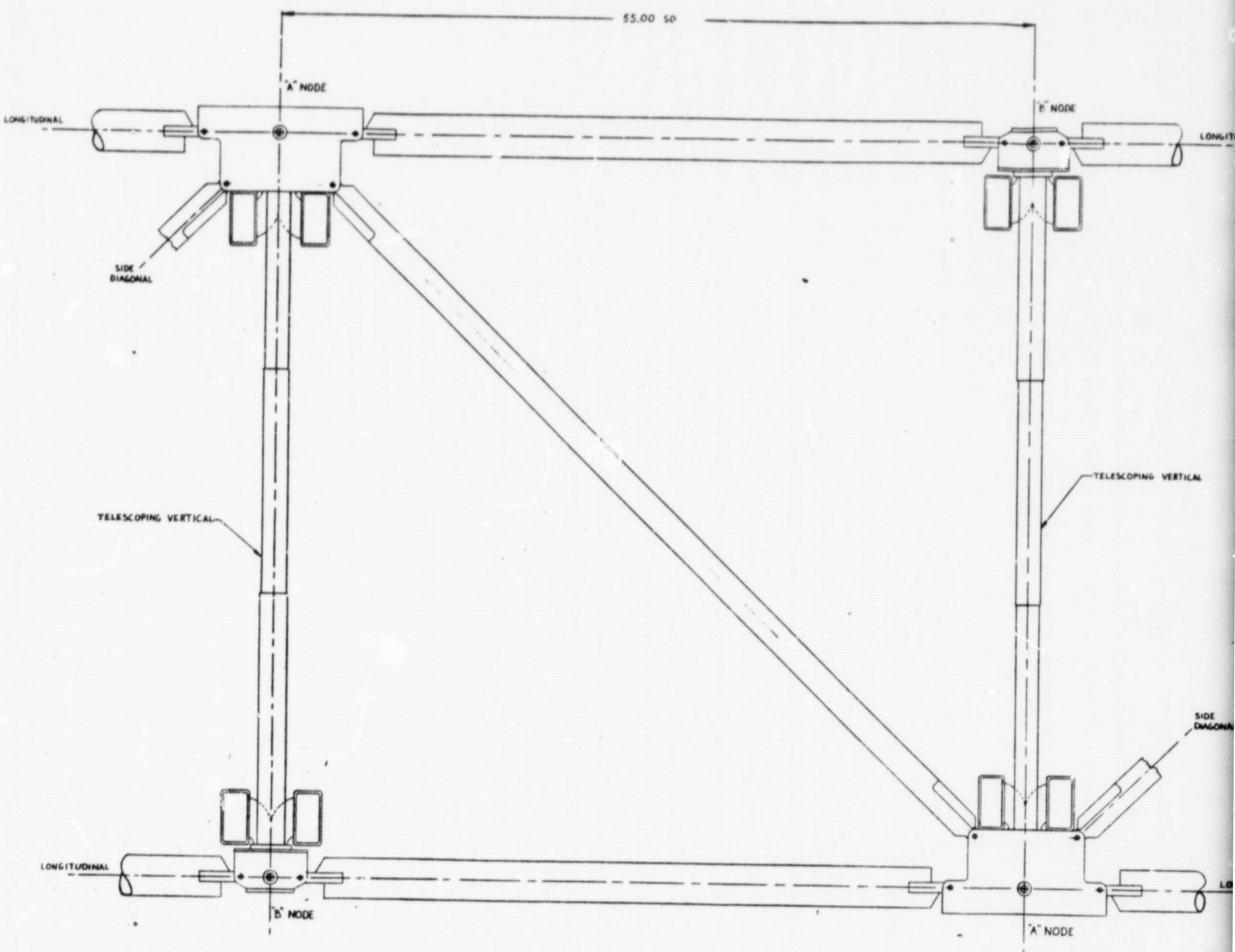

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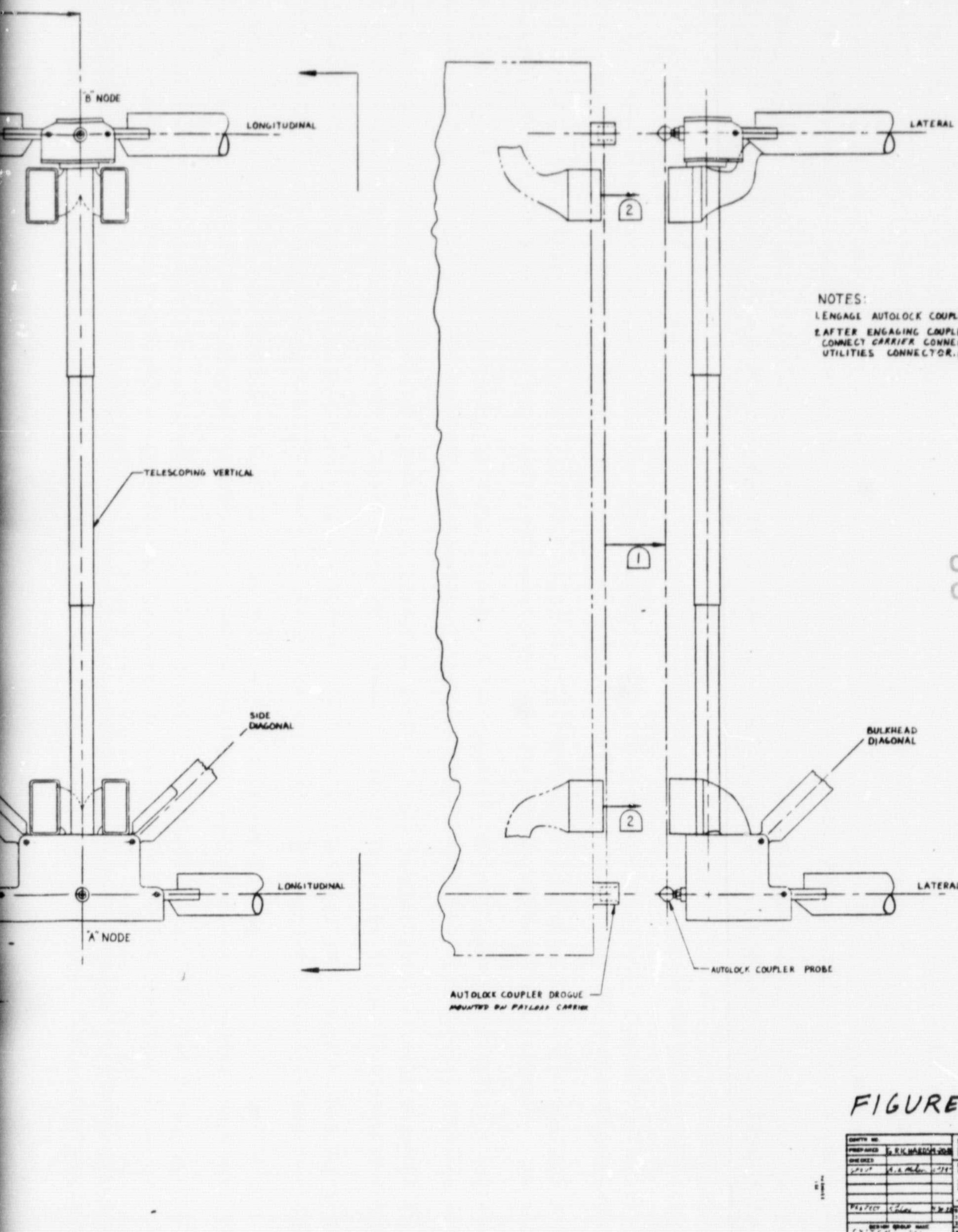

NOTES:
1. ENGAGE AUTOLOCK COUPLERS.
2. AFTER ENGAGING COUPLER MANUALLY CONNECT CARRIER CONNECTOR TO NODE UTILITIES CONNECTOR. (TEST ARTICLE ONLY)

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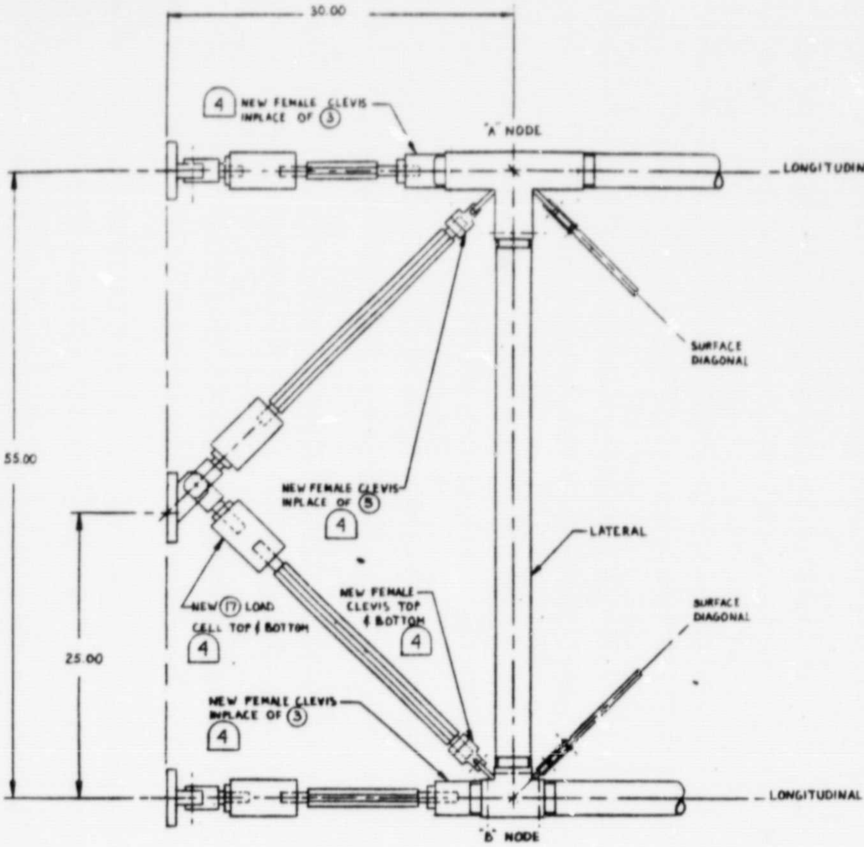
FIGURE 33

PREPARED G. RICHARDSON	VOUGHT CORPORATION
	PAYLOAD INTERFACE LAYOUT BADF GROUND TEST DESIGN — SASP DEPLOYABLE TRUSS
	80378	221-60182
	SCALE 1/2

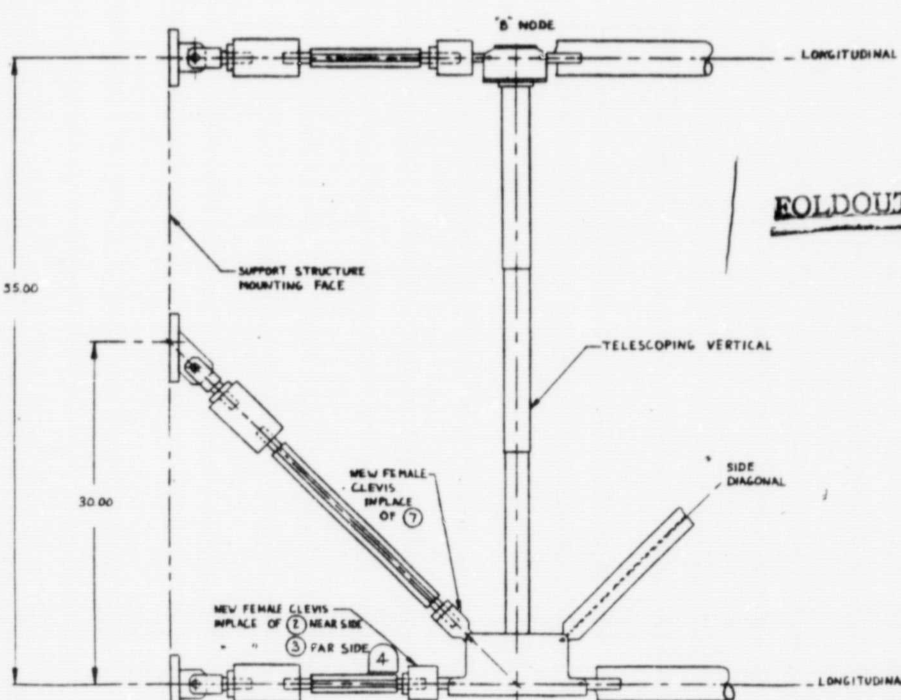
NOTES:

1. TWO LUGS WITH SUPPORT BRACKETS, LOCA
VERTICAL CENTERLINE, MUST BE ADDED TO TH
TO INTERFACE WITH THE TWO LUGS ON THE
WILL PROVIDE ROLL RESTRAINT, DURING DEPLO
IS ORIENTED AS A DIAMOND TRUSS.
2. THE DEPLOYED AND LOCKED BADF TRUSS
THREE 'A' NODES TO THE OVERHEAD CRA
3. ONE CABLE LENGTH WILL BE ADJUSTED TO
4. THE SQUARE TRUSS BASE WILL BE ALIGNED
TO IT USING MOST OF THE PARTS ON 90M
NO. 2,3,4 AND 7 CLEVIS AND ROD END FI
CLEVIS FITTINGS. TWO ADDITIONAL NO. 17
PARTS WILL BE USED AS TENSION DIAGON
OF THE TRUSS.
5. THE TWELVE AIR BEARINGS USED TO SU
DIAGONALS, DURING DEPLOYMENT AND RE
LOWER NODES ON THE SAME BULKHEAD
6. SYMBOL NO INDICATES NOTES ON THIS

MSFC DRAWING 90M07513.

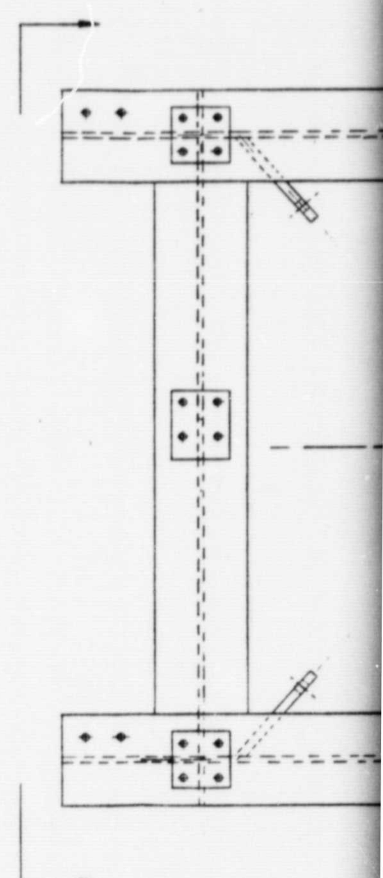


TOP VIEW



SIDE VIEW

FOLDOUT FRAME



90M07513-1
SUPPORT ROD ASSEMBLY

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S:

UGS WITH SUPPORT BRACKETS, LOCATED ONE ABOVE THE OTHER ON A
L CENTERLINE, MUST BE ADDED TO THE 90M07515-1 MOVABLE SUPPORT STRUCTURE
RFACE WITH THE TWO LUGS ON THE BADF BASE END DIAGONAL. THESE TWO LUGS
ROVIDE ROLL RESTRAINT, DURING DEPLOYMENT AND REFOLD, WHILE THE STRUCTURE
ENTED AS A DIAMOND TRUSS.

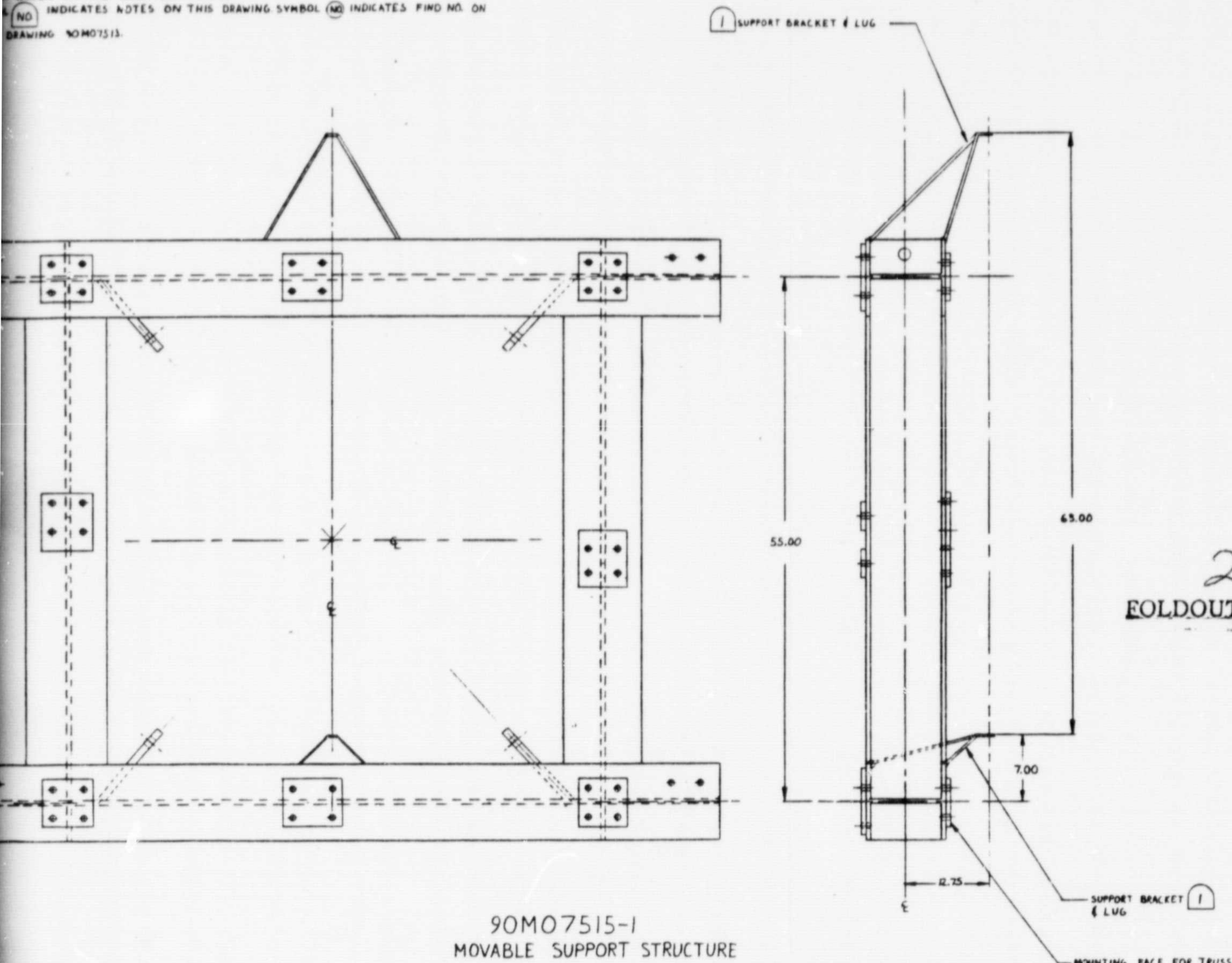
EPLOYED AND LOCKED BADF TRUSS WILL BE LIFTED BY CONNECTING
"A" NODES TO THE OVERHEAD CRANE WITH CABLES.

ABLE LENGTH WILL BE ADJUSTED TO REORIENT THE STRUCTURE AS A SQUARE TRUSS.

UARE TRUSS BASE WILL BE ALIGNED WITH THE SUPPORT STRUCTURE AND CONNECTED
USING MOST OF THE PARTS ON 90M07513-1 SUPPORT ROD ASSEMBLY. THE
,4 AND 7 CLEVIS AND ROD END FITTINGS WILL BE REPLACED BY TWO NEW
FITTINGS. TWO ADDITIONAL NO. 17 LOAD CELLS AND ASSOCIATED CONNECTING
WILL BE USED AS TENSION DIAGONALS ON THE UPPER AND LOWER SURFACES
E TRUSS.

WELVE AIR BEARINGS USED TO SUPPORT THE SIX ODD NUMBERED BULKHEAD
NALS, DURING DEPLOYMENT AND REFOLD, WILL BE USED TO SUPPORT THE TWO
R NODES ON THE SAME BULKHEADS.

NO INDICATES NOTES ON THIS DRAWING SYMBOL NO INDICATES FIND NO. ON
DRAWING 90M07513.



90M07515-1
MOVABLE SUPPORT STRUCTURE

FIGURE 34

VOUGHT CORPORATION
BASE STRUCTURE INTERFACE
BADF GROUND TEST DESIGN
- SASP DEPLOYABLE TRUSS
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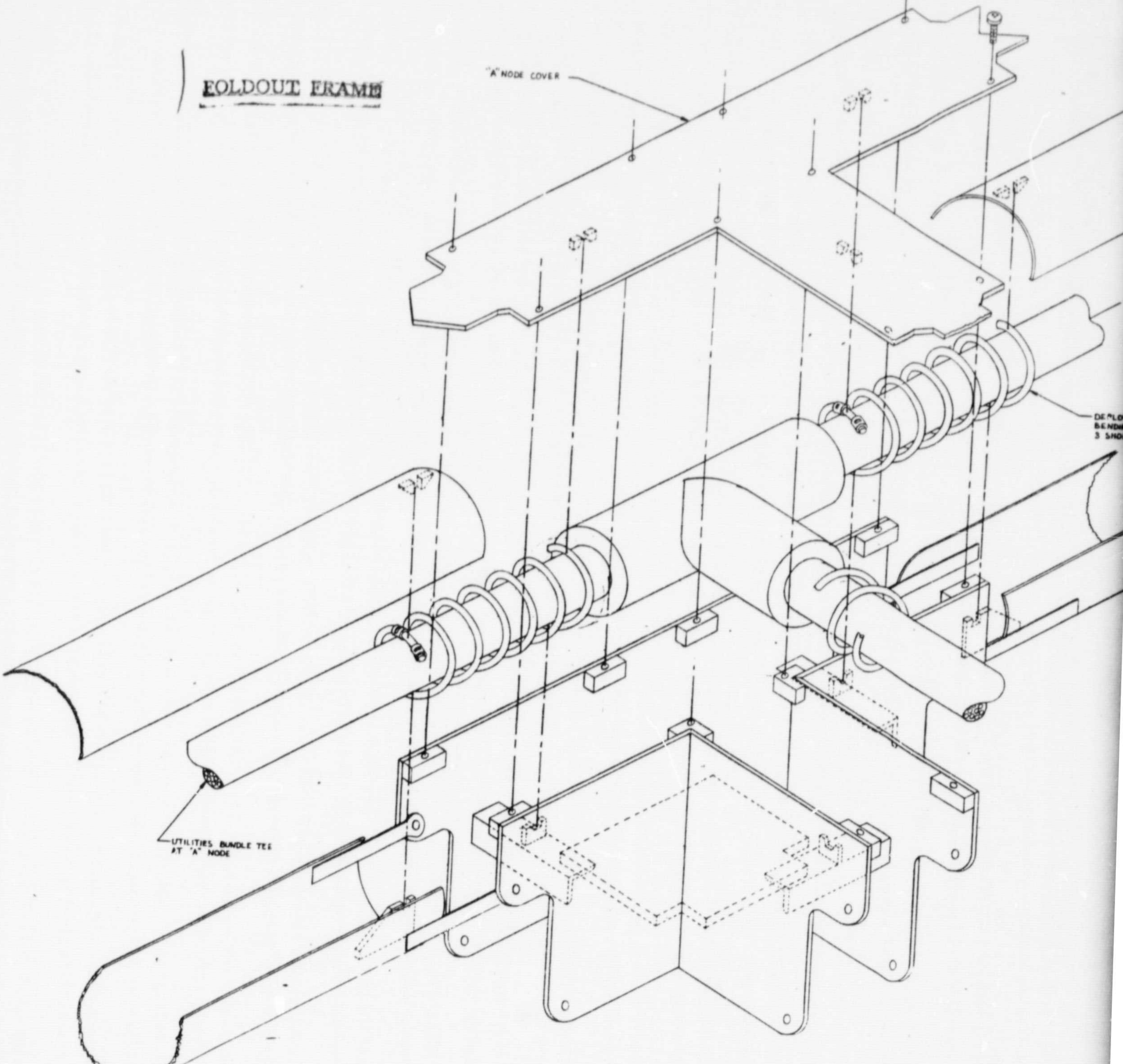
221-60182
SCALE 1/2

FOLDOUT FRAME



"A" NODE

2 FOLDOUT FRAME

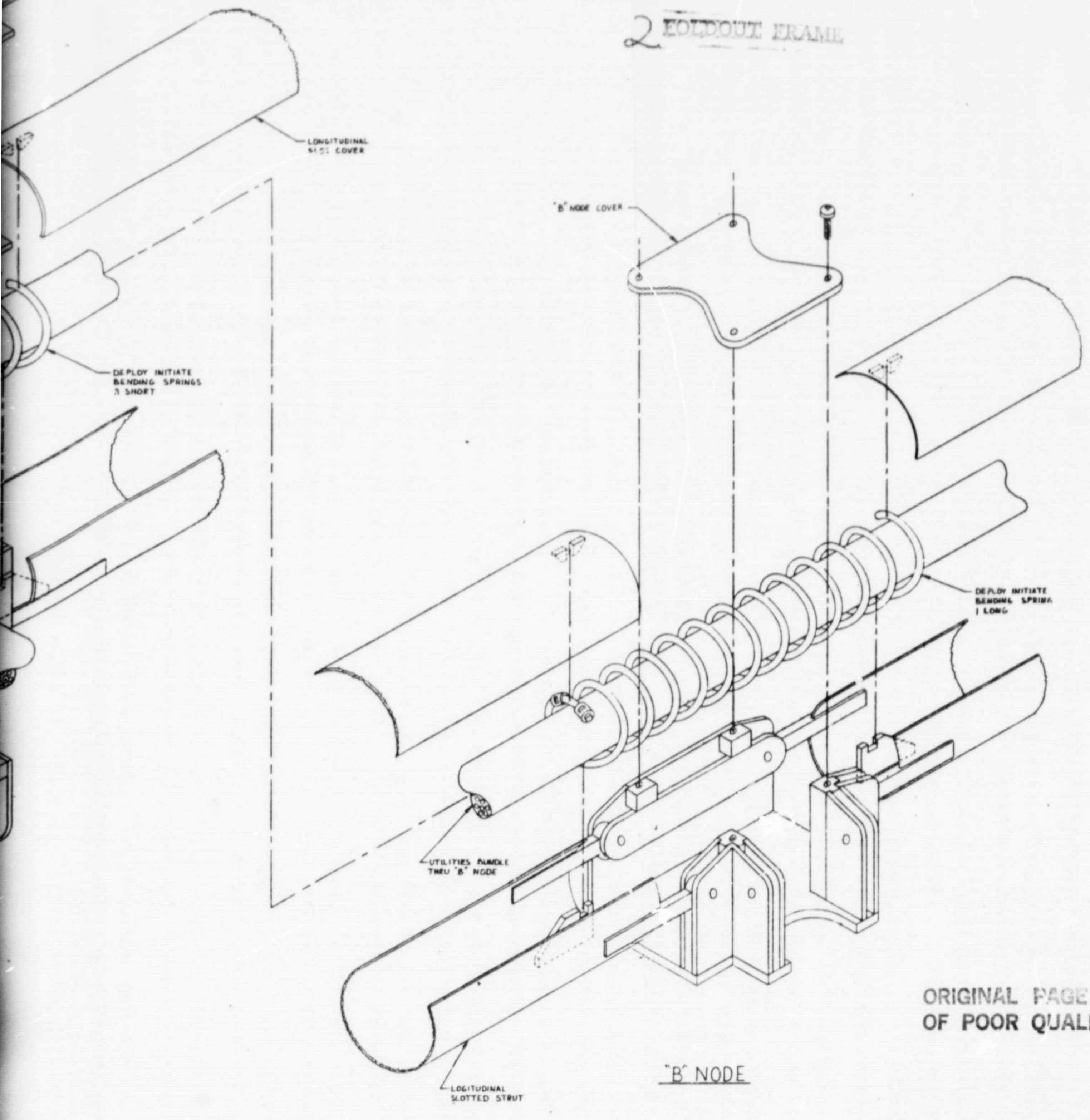


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FIGURE 35

VOUGHT CORPORATION

PREPARED G. RICHARDSON

UTILITIES INSTL. THRU NODES BADF GROUND TEST DESIGN -SASP DEPLOYABLE TRUSS

80378 221-60182

the unit weight per cell and per bulkhead, which is finally summed to the total weight of the truss. The truss total weight is the sum of the 10 cells plus one bulkhead and is about 846 lbs.

2.3 STRUCTURAL ANALYSES

Figure 36 shows the two arrangements of the ground test article that were evaluated for loads as defined in the Requirements Section 2.1. The

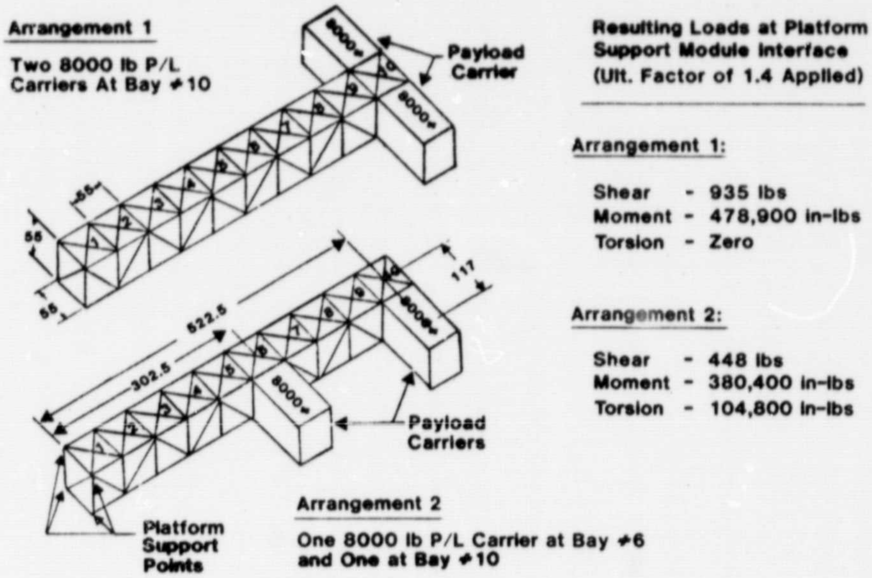

FIGURE 36

DEPLOYED TRUSS ARM CONFIGURATIONS ANALYSIS FOR STRESSES FROM 0.04g ORBIT APPLIED ACCELERATIONS

resulting evaluations provided the shear moments and torsion loads as listed in the figure . Each element of the structure was evaluated for these loads with the results that positive margins of safety were obtained in all cases. Table 5 shows the results of the structural analysis. The minimum margin of

TABLE 5

STRUCTURAL STRENGTH AND STIFFNESS ANALYSIS

GROUND TEST ARTICLE (FULLY DEPLOYED)

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- Minimum Margins of Safety for Orbit Applied Accelerations are 0.70 In. Side Diagonal, 0.36 In. Lug Bearing
- Deployment of Arm Under 1.0g Results in a 0.51 Minimum Margin on the Side Diagonal.
- For the 4.5g Shuttle Emergency Landing Condition, A Margin of 3.76 at Diagonal was Determined for the Stowed Position.
- Payload and Orbiter Berthing Loads Result in a Minimum Margin of 0.41 at the Boss Support Plate Weld.
- Bending Stiffness of the Cantilevered Arm with End Payload, $EI = 5.05 \times 10^7$ N.m^2 (1.76×10^{10} lb-in^2)
- For the Same Condition, the Fundamental Frequency was Calculated at 0.365 Hz.
- Torsional Stiffness, $GJ = 9.18 \times 10^6$ N.m^2 (3.20×10^9 lb-in^2)

safety due to Orbiter flight accelerations was 0.7 in the side diagonal and 0.36 in lug bearing. Other margins are listed for 1-g operation, Shuttle emergency landing conditions, and for payload and Orbiter berthing loads. The bending stiffness was calculated at an EI value of 5.05×10^7 Nm^2. The corresponding fundamental frequency is 0.365 Hz. In torsional stiffness a GJ value of 9.18×10^6 Nm^2 was calculated.

An analysis was also performed of the stiffness characteristics in the partially deployed configuration, as this would be significant in a flight experiment. Figure 37 shows the situation analyzed. The configuration was with the diagonals at a 45° angle, which is about 70% deployed. A NASTRAN

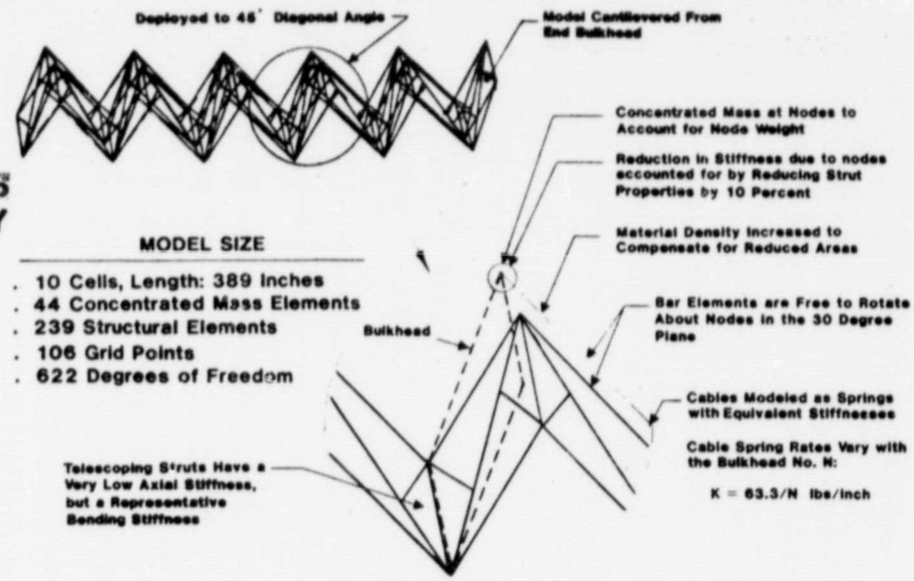
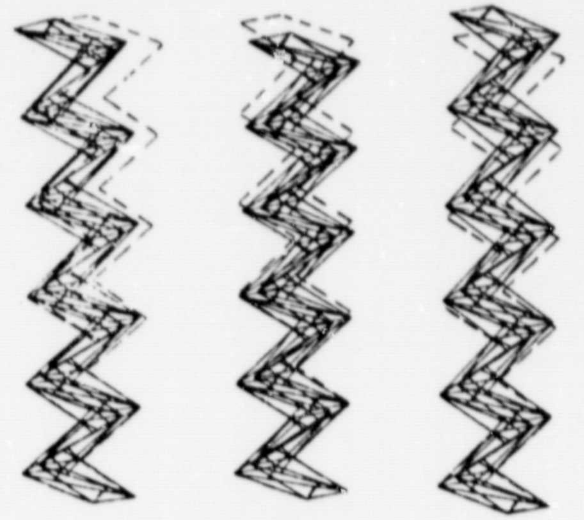


FIGURE 37

NASTRAN MODEL OF PARTIALLY DEPLOYED 10-CELL TRUSS

model consisting of 239 structural elements and 106 grid points was constructed and evaluated. Figure 38 summarizes the results of those evaluations and pictures the first three modes. Figure 39 defines the coordinate system used. The first more, Z-axis bending, has a frequency of 0.08 Hz. In Y-axis bending a frequency of 0.25 Hz was obtained. In the extensional direction, mode 3 frequency was found to be 0.36 Hz. The other frequencies through mode 10 are listed on the figure. Figure 39 also provides tabular information on stiffness, tip deflection and fundamental frequencies. Because rather large tip deflections were obtained under Shuttle Orbiter acceleration of 0.04 g with the aluminum structure, it was assessed



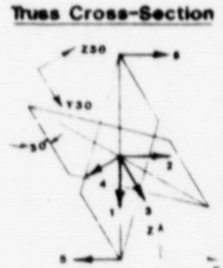
MODE NUMBER	FREQUENCY (Hz)
1	0.08
2	0.25
3	0.36
4	0.53
5	1.30
6	1.47
7	1.77
8	2.00
9	3.01
10	3.82

Mode 1 - 0.08 Hz **Z-Axis Bending** | **Mode 2 - 0.25 Hz** **Y-Axis Bending** | **Mode 3 - 0.36 Hz** **Extentional**

FIGURE 38

MODES AND FREQUENCIES OF PARTIALLY DEPLOYED GROUND TEST ARTICLE - NASTRAN RESULTS

Truss Cross-Section



Load cases 1-4 are bending due to a uniform load of 0.04g. Load case 5 is pure torsion of 7780 ft.-in applied at the end truss bulkhead.

Load Direction	Stiffness EI or GJ		Tip Deflection (Load of 0.04 g)				Fundamental Frequency	
	AL	GR/EP	Aluminum		GR/EP		AL	GR/EP
	$N.m^2$	$N.m^2$	cm	in	cm	in	Hz	Hz
	(10^3)	(10^3)						
Bending:								
1 (-Z)	11.9	72.3	178	70.2	20.3	7.99	.10	.30
2 (+Y)	28.2	145	73.4	28.9	9.83	3.87	.16	.42
3 (+Y30)	9.5	58.7	227	89.4	25.2	9.92	.08	.27
4 (-Z30)	70.3	266	24.5	9.66	4.93	1.94	.25	.57
Torsion:								
5 (± Y)	85.1	397	10.1	3.96	2.16	0.85	1.1	2.7

FIGURE 39

RESULTS OF NASTRAN ANALYSIS OF PARTIALLY DEPLOYED TRUSS

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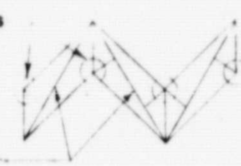
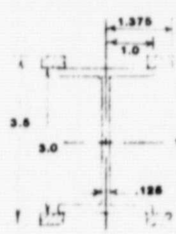
that improvements would be desirable for flight test. Otherwise, a mission constraint of no thruster firing during the deployment or retraction sequences would be required. To evaluate options that would be acceptable for flight test a graphite/epoxy model was constructed. Figure 40 shows the modifications to the design for analysis of the graphite/epoxy model. The crossectional area of the diagonals was increased and a change was made to increase the stiffness of the deployment system. This deployment system change was important because the length of the Kevlar 29 cables provides low stiffness in their extensional mode. The improved stiffness deployment system

Changes Made to Aluminum Baseline Model to Increase Stiffness

1. **Replace Aluminum with GY-70 Graphite/Epoxy (± 10 Degree Plies)**
   . **Increase Modulus from 10.5 MSI to 37.7 MSI**
   . **Decrease Density from 0.1 PCI to 0.056 PCI**
2. **Incorporate New Design with Deploy Motors at B Nodes**
   . **Double Cable Stiffness and Keep it Constant Throughout the Truss**
   . **Increasse Mass at B Nodes to Include Motors**
3. **Increase Bending Properties of Diagonal Members**
   . **Add 4 0.5 x 0.25 Sections to Existing I-Beam**





Property	Area $(in)^2$	I1 $(in)^4$	I2 $(in)^4$	J $(in)^4$
Original	.844	1.25	.167	.004
Amended	1.344	2.57	.811	.004
Percent Increase	59	106	386	0

FIGURE 40

COMPOSITE TRUSS NASTRAN MODEL

localizes the drive motor at each B node rather than utilizing a single drive motor at the base of the truss. The concept was derived in the Deployable Volumes portion of the study and is presented in Figures 49 and 50 of Section 3.5. Resulting changes to the properties of the truss are also listed in Figure 40. Figure 39 shows that the frequencies are considerably higher for this new configuration and the tip deflections are 25 cm or less, which should be satisfactory for a flight experiment.

2.4 DYNAMIC AND THERMAL DISTORTION ANALYSIS

While the Table 2 Misalignment and Distortion specifications are interpreted as applying strictly to an actual flight article, since thermal distortions within $\pm$ 0.1° cannot be obtained under severe earth orbital conditions with an aluminum truss, tip deflection characteristics under dynamic and thermal loadings were calculated in order to bound the expected behavior of an aluminum structure were it to be flown.

With the maximum payloads arranged as previously shown in Figure 36, and the Table 5 stiffness properties of the BADF truss ground test article, linear accelerations to produce $\pm$ 0.1° tip distortions were calculated. An acceleration of 1.4×10^{-2} g was determined to result in 0.1° distortion under the Arrangement 1 bending loading, while a 2.2×10^{-2} g acceleration is necessary to result in 0.1° distortion under the Arrangement 2 torsional loading. Maximum maneuver accelerations estimated for the Ref. (1) ASASP, for comparison, were estimated to be 1.5×10^{-3} g.

Figure 41 shows the results of the thermal distortion analysis. First, orbital temperature transients were considered. Two thermal coatings applied to the truss were evaluated. A thermal coating with approximately equal solar absorptivity and emissivity values of 0.25 (a leafing aluminum silicone) was evaluated to have a temperature transient of about 22°C as it

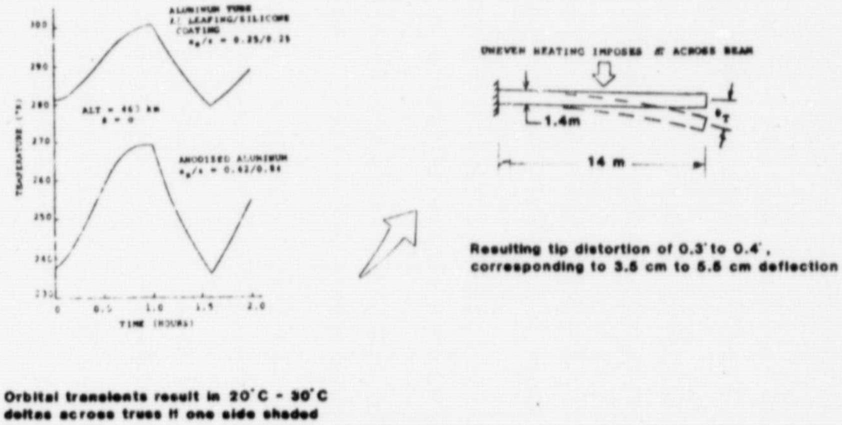


FIGURE 41

THERMAL DISTORTION OF ALUMINUM TEST ARTICLE UNDER ORBITAL CONDITIONS

transverses an orbit. A tube with an anodized aluminum surface having solar absorptivity and emissivity values of 0.42 and 0.84, respectively, was also analyzed. While the maximum temperatures reached with the anodized aluminum are lower, the variation from hot to cold orbital conditions is about 33°C. If the opposing struts on the truss were shaded, unequal heating could be imposed and thermal distortions would result. With maximum uneven heating of 20° to $30^{\circ}C$, analysis showed the tip of a 14 m long beam (approximately the length of the test article) would deflect about 0.3° to 0.4° (3.5 to 5.5 cm). This would be a cyclic distrubance and could provide difficulty in payload pointing. If such distortions could not be handled by the payload pointing system other strategies might be necessary, such as wrapping the struts in multilayer insulation. A more desirable solution would be fabrication of the truss from graphite/epoxy.

3.0 DEPLOYABLE VOLUMES CONCEPT DEVELOPMENT

Future missions such as a Space Station will require pressurized volumes for use as crew quarters, manned laboratories, and transfer tunnels. In addition, hangars for tasks to be performed on Orbital Transfer Vehicles (OTV's) and maneuvering vehicles and/or payloads are projected, and may be pressurized or unpressurized. To minimize launch costs and enable use of volumes greater than those which can be transported by the Space Shuttle Orbiter, it is important to consider deployable volumes. During Part 1 of this study various concepts were evaluated, and the deployable truss/inflatable bladder approach was selected as having major potential for deploying large volumes with deployed/stowed ratios as great as 200:1. Part 2 was initiated to evolve the Part 1 truss/bladder concept for habitat and hangar modules. Emphasis was placed on buildup and assembly considerations, where it was desired to maintain the large deployed/stowed volume ratio achieved in Part 1 while minimizing the use of EVA and the RMS. Other considerations to be addressed during Part 2 included Orbiter packaging and launch suitability, compatibility with the Space Station, material suitability for long-term duration in Low Earth Orbit (LEO), and micrometeoroid impacts. Special considerations for the habitat were crew accommodation, including pressure maintenance and radiation shielding; equipment accommodation; crew ingress/egress; design redundance; and heat rejection. Considerations unique to the OTV hangar included equipment storage for the OTV; servicing/refueling; ingress/egress of the OTV; and provisions of work platforms, lighting, and electrical power. In addition, it was desired for both applications to evolve concepts for integrating the pressure bladder and thermal/meteoroid blanket with the truss for automatic deployment, and to select the best truss design.

3.1 MISSION SELECTION

During Part 1 studies the NASA-MSFC Phase III SAMSP conceptual design (Ref. 2) was taken as a representative Space Station which could utilize the benefits of deployable volumes for an OTV hangar, habitat/experiment modules, and transfer tunnels A similar concept which could also benefit is the Reference 8 Space Operations Center (SOC). In Figure 42, two other potential missions for the habitat are illustrated. One is a 20-ft diameter module currently under study (References 2, 9) which could be transported to orbit in an aft cargo compartment attached to the base of the Shuttle external tank. This module could be applied as either a service

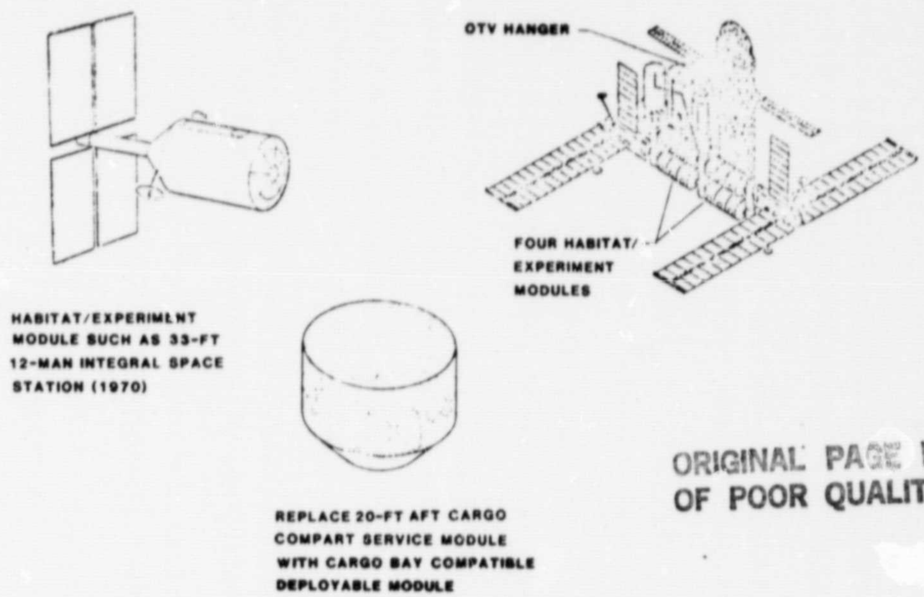


FIGURE 42

POTENTIAL MISSIONS FOR DEPLOYABLE VOLUMES

module or a crew habitability module. Its volume is about 170 m^3 (6000 ft^3), compared to about 113 m^3 (4000 ft^3) for a stretched Spacelab Module. Use of the deployable volume concept would allow a module of this diameter to be easily packaged in the Shuttle Orbiter cargo bay. A more substantial mission challenge would be a very large Space Station module, such as represented by the 10m (33-ft) diameter 12-man Integral Space Station (ISS) habitat/experiment module studied through Phase B in the early 1970's (Reference 10). This ISS module is very large, with about 1050 m^3 (37,000 ft^3) pressurized volume, and four floors for crew and mission accommodation. Provisions for berthing four Spacelab-like pressurized experiment modules on the sides are also included. Being significantly larger than the Phase III SAMSP (about 450 m^3 (16,000 ft^3) habitat/experiment area), the ISS module was chosen as a representative large volume which would both; (1) demonstrate the capabilities of the deployable volume concept to accomplish things using the Space Shuttle which could not otherwise be accomplished, and (2) provide a mature (Phase B) design basis which would furnish representative mission, subsystem, and crew accommodation designs without necessitating detailed subsystems studies under the current effort.

Representative OTV design concepts were also selected for consideration while evolving the deployable hangar. Figure 43 pictures the three chosen; Centaur G, Centaur G', and a reusable OTV concept used in SOC hangar studies. These OTV designs differ in size, interface (aft cradle support vs docking adapter) and tasks to be performed.

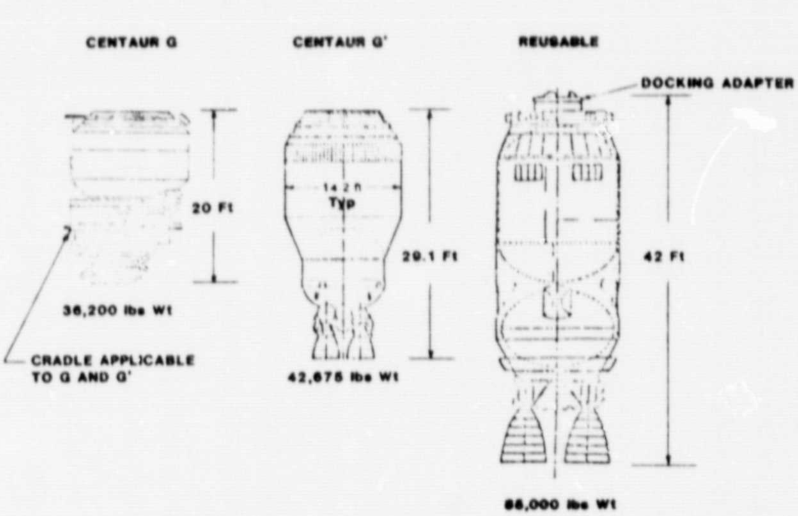


FIGURE 43

REPRESENTATIVE ORBITAL TRANSFER VEHICLES

3.2 GUIDELINES AND REQUIREMENTS FOR DEPLOYABLE VOLUMES

Guidelines and Requirements for deployable volume studies were derived from review of prior large platform (Ref.1) and Space Station (Refs.

2, 8, 10, 11, 12) studies and current considerations. Table 6 contains general guidelines and requirements. Specific structural and mechanical

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TABLE 6

GENERAL GUIDELINES AND REQUIREMENTS FOR DEPLOYABLE VOLUMES

- **Evolve deployable truss, flexible bladder concepts from Part 1**
- **Provide compatibility for application to a wide range of emerging Space Station concepts**
- **Consider Centaur and reusable OTV concepts**
- **Consider:**
  - . **Pressurized manned habitat/experiment modules**
  - . **Pressurized and unpressurized OTV hangar modules**
- **Low Earth Orbit (LEO)**
- **Initial delivery may be "dry" or "wet"**
- **Retraction not required**
- **Compatible with Shuttle for launch and EVA/RMS operations**
  - . **JSC 07700, Vol. XIV - Payload Accommodation Handbook**
  - . **Max stowed dimensions: 4.3m (14 ft) dia envelope, with protuberances 16.2m (53.25 ft) length, with docking module & EVA**
  - . **Max weights: 29,485 kg (65,000 lb) max launch 14,515 kg (32,000 lb) max planned landing**
  - . **On-orbit attached operation: Vernier thrusters only**
- **Consider deployable volume diameters, lengths, and weights up to limits of Shuttle compatibility**
- **Operational life of 10 years with maintenance**
- **Crew changeout 90-180 days**

requirements are presented in Table 7 and Figure 44, and safety requirements in Table 8. Berthing loads given in Table 7 are based on RMS capabilities. Docking closing velocities presented in that table are from Ref. (1) and were based on consideration of prior space experience. Resulting loads depend on acceleration rates arising from the docking impact, and the Space Station mass. A maximum load of 1360 kg (3000 lb) was calculated assuming a 136,200 kg (300,000 lb) Space Station with a 0.01-g acceleration. Docking moment applied at the interface depends on spring rate of the structure. A limiting case moment applied by the Orbiter was suggested in Ref. (1) to be 162,700 N.m (120,000 lb-ft), due to Orbiter strength considerations. Since this moment is quite high and can be designed around, the current approach taken was to evaluate the maximum moment which can be accommodated by the deployable truss structure with only modest localized structural enhancement.

Allocation of functions/equipment among Space Station modules and physical/performance characteristics of subsystem, experiment, and crew accommodation equipment is highly mission and design dependent. Representative selections and characteristics were determined from prior studies, with emphasis on the 12-man ISS for the habitat/experiment module.

TABLE 7

STRUCTURAL/MECHANICAL GUIDELINES AND REQUIREMENTS FOR DEPLOYABLE VOLUMES

Pressure Level

- **Habitat/Experiment Module:** Nominal 8 psia - 14.7 psia
  Emergency 5 psia - 8 psia
- OTV Hangar: Unpressurized
  Pressurized: 8 psia - 14.7 psia nominal
  5 psia - 8 psia emergency

Micrometeoroid and Debris Protection

- Probability of no penetration of 0.95 for 10 years
- Meteoroids per NASA SP 8013
- Debris per Kessler 1978 model

Stiffness

- First mode frequency >0.1 Hz
- Dynamic isolation from any high frequency rotating equipment

Strength

- Withstand acceleration of 0.02-g during attitude control, reboost, or Orbiter docking with Station
- Withstand docking impact of Orbiter with deployable volume under conditions of:
  - Closing velocity of 0.15 m/s (0.50 fps)
  - Angular velocity of 0.2 deg/sec
- Withstand berthing impact (using manipulator) conditions of:
  - 182 kg (400 lb) any direction contact load
  - 1627 N.m (1200 ft-lb) any direction interface moment

Hatches and Passageways

- Minimum 1 m (40 inch) diameter (Orbiter "D" hatch) - larger permissible

Safety Factors

- Unpressurized Structure - 1.5 on ultimate strength
  1.1 on yield strength
- Pressurized Volume (Metallic) - yield = 1.65 x limit pressure
  burst = 2.0 x limit pressure
- Pressurized Volume (Glass Window Panes) - burst = 3.0 x limit pressure
- Pressurized Volume (Flexible Nonmetallics) - burst = 5.0 x limit pressure
- Redundant Window Panes

Leakage

- Atmospheric gas leak rate less than 3.3×10^{-3} kg/day/m^3 (2.0×10^{-4} lb/day/ft^3)
- Pressure shell design to facilitate repair

TABLE 8

SAFETY GUIDELINES AND REQUIREMENTS FOR DEPLOYABLE VOLUMES

Space Radiation Protection

. **Allowable Dose:**

	Limit Dose (REM)		
	30 Day	Quarterly	Yearly
Skin	75	105	225
Eye	37	52	112
Marrow	25	35	75

. **Shielding of 0.5 - 1.3 gm/cm^2 required most LEO orbits**

Fluids

. **Only water and air ECLSS fluids in pressurized volume**

. **No potentially explosive containers inside pressurized volume**

Internal Temperatures

. **45°C (113°F) maximum touch temperature**

Egress

- **Alternate egress routes during both buildup and permanent occupancy**
- **Emergency EVA/IVA equipment stowage allocation in each pressure isolatable volume**
- **EVA hatches open either side: close in direction of positive pressure differential. IVA hatches open either way: capability for pressure equalization.**

Redundancy

- **Compartmentation of the Space Station providing two separate pressurized habitable volumes**
- **Redundant safety critical subsystem equipment and utilities located in separate areas**
- **Failure of a single structural member shall not place crew in immediate jeopardy**

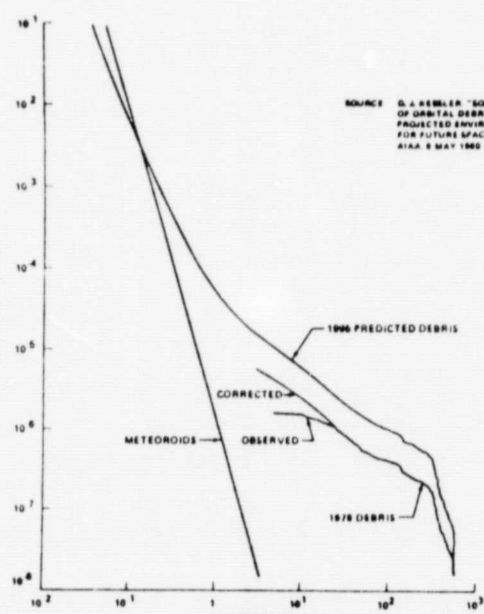

FIGURE 44

METEOROID AND DEBRIS FLUX BETWEEN 600 AND 1100 km ALTITUDE

In general, the habitat module was required to fit the prior patterns of total volume vs crew size presented in Figure 45, and the Celentano free volume requirements given in Figure 46.

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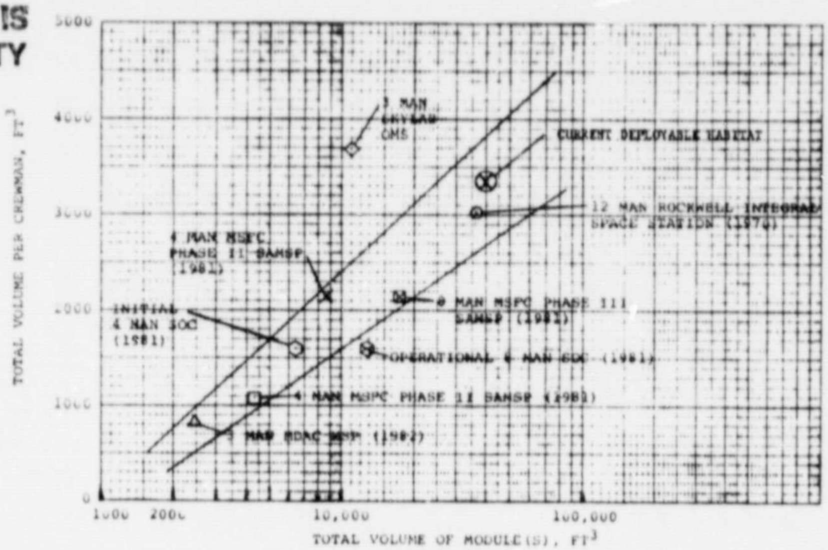

FIGURE 45

RELATIONSHIP BETWEEN TOTAL VOLUME OF SPACE STATION MODULES AND NUMBER OF CREWMEN

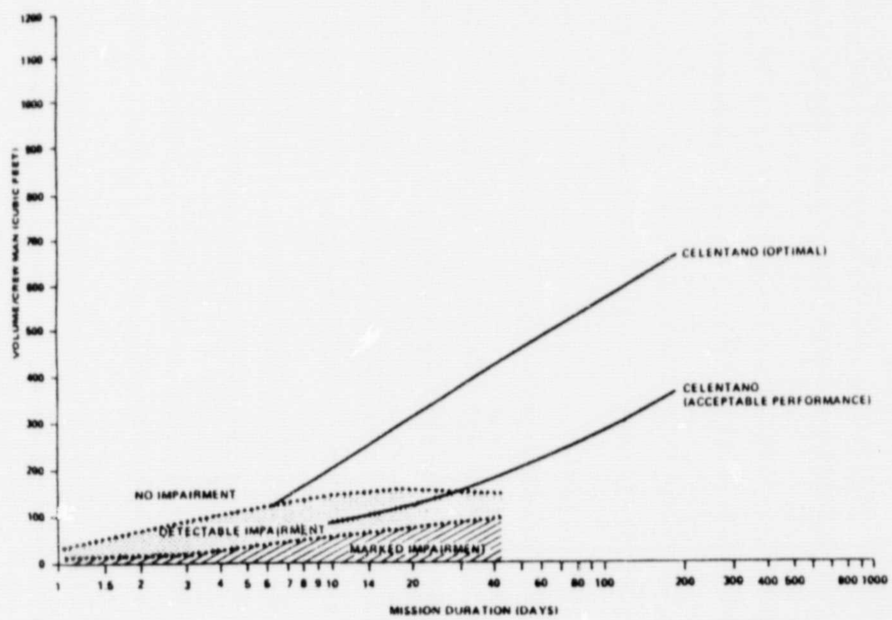

FIGURE 46

RELATIVE HABITABILITY FOR 4 MAN/90 DAY MISSION

Thermal management requirements which have an impact on the current deployable volume study are maintenance of cabin wall temperature within acceptable limits and provision of heat rejection capability. While cabin wall temperature is a complex function of both the Environmental Control/Life Support Subsystem (EC/LSS) design and the external insulation system design, the only variable which need be addressed here is the insulation system. (It can safely be presumed that an adequate EC/LSS will be incorporated as long as the deployable volume provides a suitable configuration and space to accommodate it.) The design requirement is then maintenance of a cabin wall temperature between about $15^{\circ}C$ ($59^{\circ}F$) and $45^{\circ}C$ ($113^{\circ}F$), consistent with avoidance of condensation and the pain threshold, respectively. Within these limits, the insulation must be sufficient to avoid major heat loss or gain to the environment.

Heat rejection requirements are highly dependent on the overall Space Station design philosophy and the mission experiment complement. In one extreme, all the waste heat is transported to a centralized deployed radiator located on a module such as the Power Module. The other extreme is decentralized heat rejection, with each module responsible for its own heat rejection. Various shades inbetween are also practical alternatives. Missions with a large percentage of high power experiments, such as space processing, will have much greater heat rejection requirements than, say, science experiments. Habitat/experiment module heat rejection requirements from some prior studies are about 5 kW for the MDAC Manned Space Platform (Ref. 11), about 13 kW for the NASA-MSFC Phase I SAMSP (Ref. 2), and about 35 kW for the 12-man ISS (Ref. 10). Because of the design/mission sensitivity of the heat rejection needs, the requirement imposed during the current study was to maximize external body area available for radiators, consistent with the overall deployable volume approach.

Another requirement with potential substantial influence on deployable volume design is the provision of adequate Van Allen radiation shielding to prevent an excessive dose to the crew. The required shielding to avoid over-exposure has been the subject of a detailed evaluation during the 1977 and 1978 Space Construction Base (SCB) space station study conducted by McDonnell Douglas (Ref. 12). That study evaluated low earth orbit missions ranging from 28.5° to 55° inclination at orbital altitudes ranging from 400-500 km. This includes the range of orbital conditions considered by the NASA-MSFC inhouse study for the SAMSP (Ref. 2) where a reference orbit of 390 km and a reference inclination between 28 and 56° was considered. In defining shielding requirements for the SCB study McDonnell Douglas evaluated the radiation dose accumulated by the skin, eyes and bone marrow, and determined that the skin is most difficult to protect. Their studies looked at mission durations from 30 days to 90-180 days. The allowable dose was 105 REM over a period of 90 days or 210 REM for a 180 day mission. This is equal to a 1.16 REMs per day allowable dose for the skin. The SCB study considered module shielding in the range of 0.5 gm per sq.cm to about 1.4 gm per sq.cm, and determined that for an orbital inclination of 28.5^{o} shielding of 0.5 gm per sq.cm is more than adequate for the 90-180 day mission (only 65% of the allowable dose). That margin allowed sufficient allocation for crew EVA operations, where the dose received is much higher. At the 55^{o} orbital inclination and 500 km altitude the condition was much more severe. Their study showed that if no EVA were allowed the shielding requirement would be on the order of 0.8 gm per sq.cm. From an analysis of the influence of EVA on the module shielding, McDonnell Douglas concluded that for a 55^{o} orbit at 450 km altitude about 1.1 gm per sq.cm module protection is desirable. This level of protection was in conjunction with a recommendation for additional protection for the EVA crewmen, and short and well scheduled shifts. It was estimated from their results that 1.3 gm per sq.cm would be required for a 500 km altitude at 55^{o} inclination. It was concluded for the current study that required protection against the Van Allen radiation is in the range of somewhat below 0.5 gm per sq.cm to a maximum of 1.3 gm per sq.cm, as given in Table 8.

3.3 APPROACH FOR STOWAGE, DEPLOYMENT, AND BUILDUP

The trade tree shown in Figure 47 was constructed to evaluate options for buildup of the deployable habitat. Many of the considerations also apply to the hangar. The first level of options considered was the size of the loading hatch to be provided for on-orbit installation of internal subsystems and equipment. The standard 1 m docking hatch requires minimal space in the cargo bay, but severely restricts the size of equipment packages which can be loaded through it. A rigid 4 m hatch represents about the largest size which can be stowed in the cargo bay, is big enough for passage of all equipment foreseen, and allows limited modularization. A full diameter clamshell permits RMS installation of large groups of equipment mounted on skids, but requires working in an unpressurized environment.

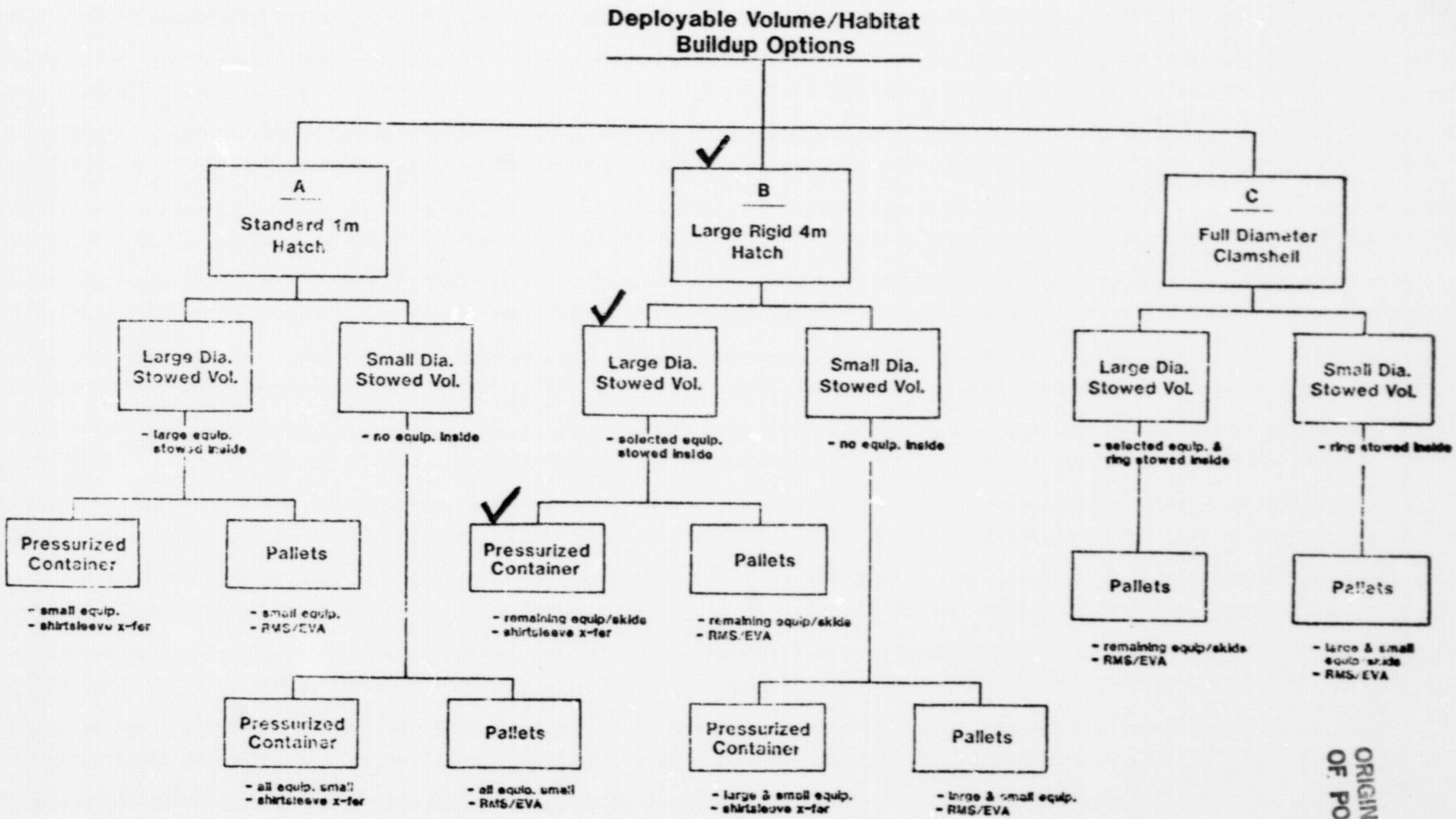

FIGURE 47

TRADE TREE FOR PACKAGING CONCEPT

The second level of options considered was the stowed diameter of the truss structure, either as small as possible to minimize volume in the cargo bay, or as large as possible (consistent with the available cargo bay payload envelope) to permit stowage of equipment inside the retracted truss. The large stowed diameter also facilitates combined use of the central structure for both equipment mounting and as a rigid backbone to support the truss/bladder structure in the cargo bay.

The final level of options considered was whether to stow equipment (for subsequent installation into the deployed volume) in a pressurized container or an open pallet. Either option allows some modularization and use of skids, depending on loading hatch size selection. The pressurized container facilitates shirtsleeve transfer during buildup, while an unpressurized pallet is more compatible with RMS aided operations but requires EVA.

The options selected, indicated by check marks on the figure, were to stow equipment in a pressurized container concentric within the stowed structure, and to provide it with as large a loading hatch as possible. This rigid core container serves both as a storage space for structural elements required for initial habitat deployment/assembly, and as a fully outfitted habitable core module which will permit limited activation of the deployed volume upon its initial Shuttle delivery flight.

For the deployable hangar, a somewhat different stowage configuration was selected because it was necessary to provide side-by-side mounting of the folded cylinder halves in the cargo bay in order to deliver the entire hangar in one flight. While the idea of mounting equipment concentric within the folded truss was retained, the 1.27m (4.17 ft) diameter tunnel was chosen as the structure to define the core container diameter. Pressurization of the container is not needed. This led to separately stowed 1.65m (5.43 ft) diameter airlocks, packaged parallel to the folded hangar truss sections in the cargo bay. RMS/EVA installation of the airlocks subsequent to hangar structure deployment is required.

3.4 SELECTION OF TRUSS CONCEPT

At the close of Part 1 of the study two bidirectionally folding truss concepts had been examined. One, the Biaxial Double Fold (BADF) truss was evaluated as an extension of the concept used for the deployable truss beam. It was possible to obtained deployable volume diameter ratios between about 8:1 to 16:1 with this truss, as indicated in Figure 48. There is also a length change with the BADF truss as the volume is deployed (length shrinks at

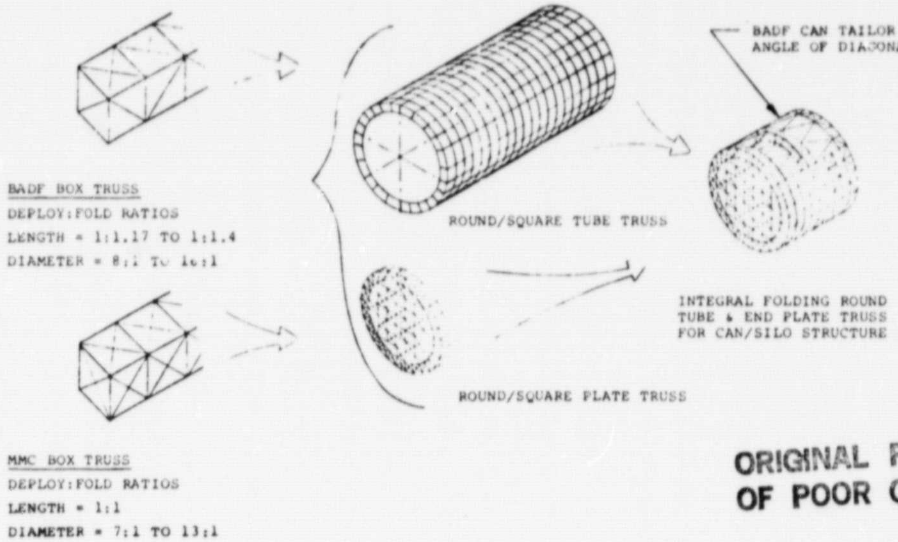

FIGURE 48

CAPABILITIES OF DEPLOYABLE TRUSS OPTIONS

a ratio somewhere between 1.17:1 and 1.4:1). The other truss candidate was the Martin Marietta Box Truss. With the Box Truss it is possible to deploy volumes with diameter ratios between 7:1 and 13:1. Its length does not change with deployment. As indicated in Figure 48, either of these trusses can deploy into a cylindrical shape or into a round or square plate truss; or they can be designed to deploy integrally into a round tube with an end plate. The BADF can be arranged with the diagonals oriented at selected angles to tailor the length change during deployment. In the current conceptual development effort it was desired to examine the features of both truss concepts and select one for further development. Table 9 makes this comparison. In addition to the difference in length change of the two concepts, it is shown that the Martin Box Truss requires actuation at each node where the BADF requires actuation at every other node. The Box Truss has knee joints on both longitudinals and laterals, as compared to one piece longitudinals and laterals on the BADF resulting in about 33% fewer joints in the load paths. Each of the truss concepts can accommodate utility integration; greater

TABLE 9

SELECTION OF TRUSS STRUCTURE FOR DEPLOYABLE VOLUMES

MMC BOX TRUSS	**VOUGHT BADF**
. No Length Change During Deployment	. Length Decrease During Deployment - Can Be Tailored
. Deployment Actuation Required Every Node	. Deployment Actuation Required Every Other Node
. Knee Joints On Longitudinals & Laterals	. I-Piece Longitudinals & Laterals -33% Fewer Joints In Load Path
. Utility Integration Possible	. Increased Utility Integration Capability

Select BADF -

Driver Is Bladder Length Matching During Deployment

capability for this integration exists for the BADF. A selection to pursue the BADF was made, mainly because of its capability for tailoring the length change during deployment to match the length change of the bladder, thereby facilitating integration of the bladder directly with the structure.

3.5 TRUSS DEPLOYMENT CONCEPTS

Because of the many cells involved it is not practical to deploy the truss volume with a cable system originating at one point, as was done with the truss beam. Figure 49 illustrates one of the concepts evaluated for deployment of the deployable volume truss. This concept utilizes multiple

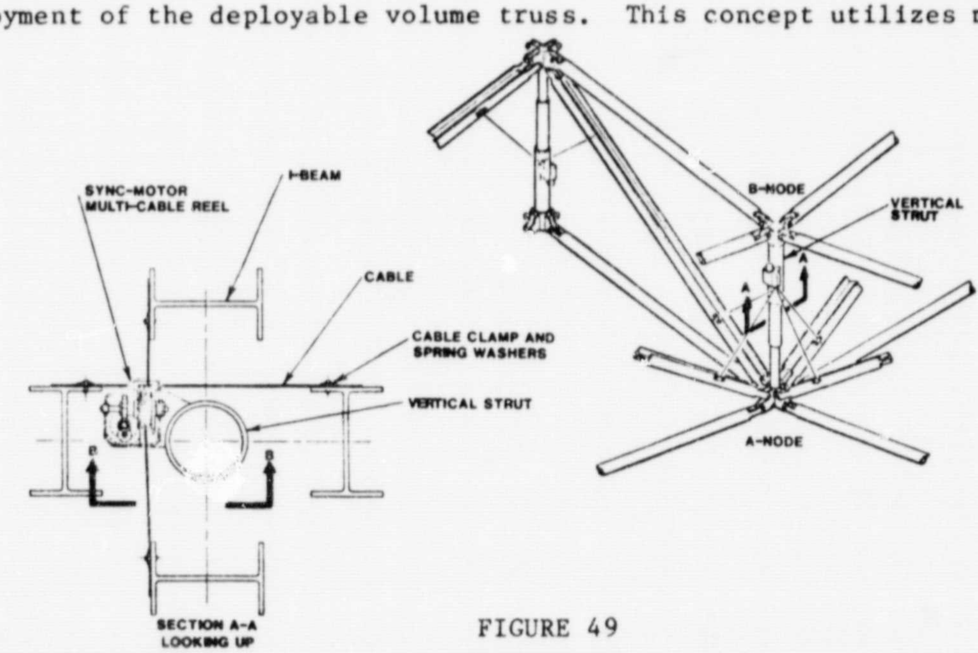

FIGURE 49

MULTIPLE MOTOR/CABLE REEL CONCEPT FOR DEPLOYING LARGE BADF TRUSS synchronous motors, one located at each B node and controlling four cables each. This provides highly localized deployment and retraction forces to a few short cables, completing circumventing problems of cable stretch. The design also features significant redundancy. If a motor were to fail, spring energy on the surrounding nodes (also acting to unfold the same diagonals) would provide sufficient force to overcome the hangup. Since there are three or four nodes surrounding each individual node, a sufficient force is available to overpower a failed motor/cable reel. A cable clamp design has been incorporated to allow slip of each cable at a certain level selected to avoid damage. Figure 50 provides additional detail for the multiple motor cable reel concept showing the small synchronous motor and worm gear drive mounted on the side of the vertical strut. Four cables are actuated through a

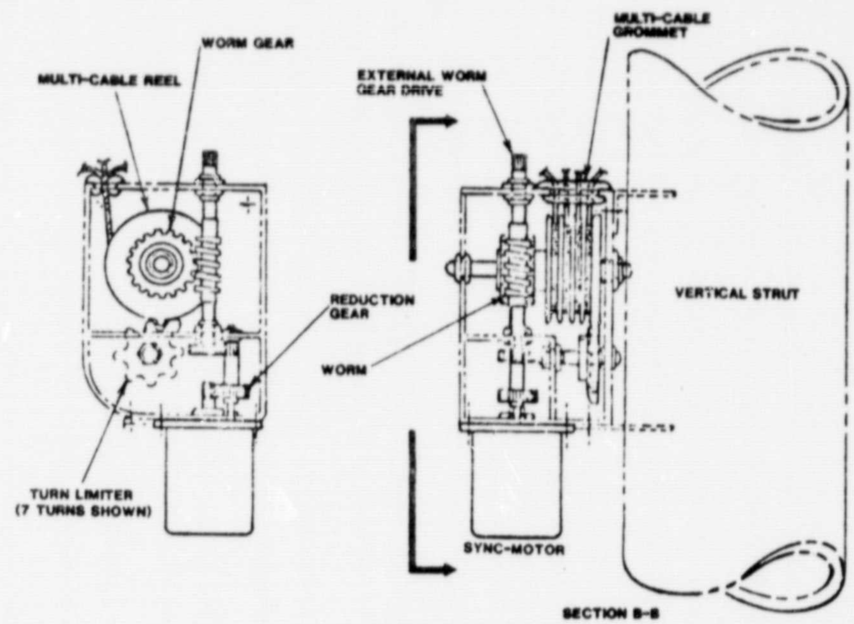

FIGURE 50

MULTIPLE MOTOR/CABLE REEL CONCEPT FOR DEPLOYING LARGE BADF TRUSS

grommet by a synchronous motor/worm drive mechanism incorporating a turn limiter. A single variable frequency-source powers all the motors. An alternate concept is pictured in Figure 51, where multiple motors are again used but the mechanism is now located on the A nodes and a jack screw actuates a linkage and releases a deployment lock. If a motor stalled in this concept it would be overpowered by the 3 or 4 adjacent motor/mechanisms operating in

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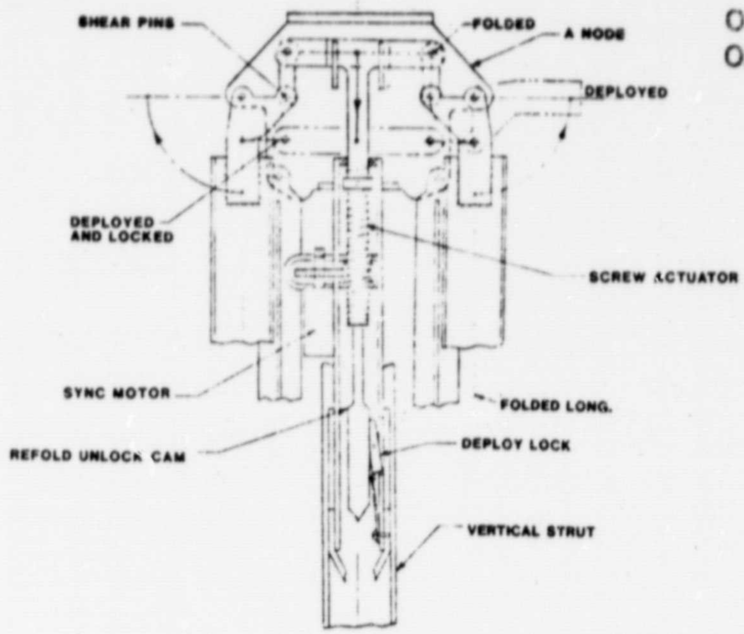

FIGURE 51

MULTIPLE MOTOR/MECHANISM CONCEPT FOR DEPLOYING LARGE BADF TRUSS

parallel with it, and shear the pins in its drive cranks. Because of the linkages involved and the short moment arms they act through, this motor/mechanism concept does not provide the overall stiffness to the deployed structure that the localized cable concept of Figures 49 and 50 provides. The mechanism of Figure 51 also precludes internal utilities routing through the A nodes.

3.6 CONCEPT FOR FOLDING AND DEPLOYING OF BLADDER AND INSULATION BLANKET

A concept for preattaching the bladder to the deployable truss and deploying the two simultaneously is illustrated in Figure 52. The figure also shows attachment and deployment of the external insulation blanket with the truss. The fully folded configuration, illustrated in the center of the figure, shows a bladder pleated longitudinally and folded concentric with the canister core module, and a similar installation of the pleated external thermal/meteoroid blanket A blowup of this configuration is illustrated by the arrow. Half deployed, the pleats begin to unfold and, finally, at full deployment the pleats have totally unfolded and form a smooth surface. Since both the bladder and the structure change length when deployed, it is possible to attach the bladder and external blanket to the structure only at one longitudinal station; this is done in the center of the structure to a single

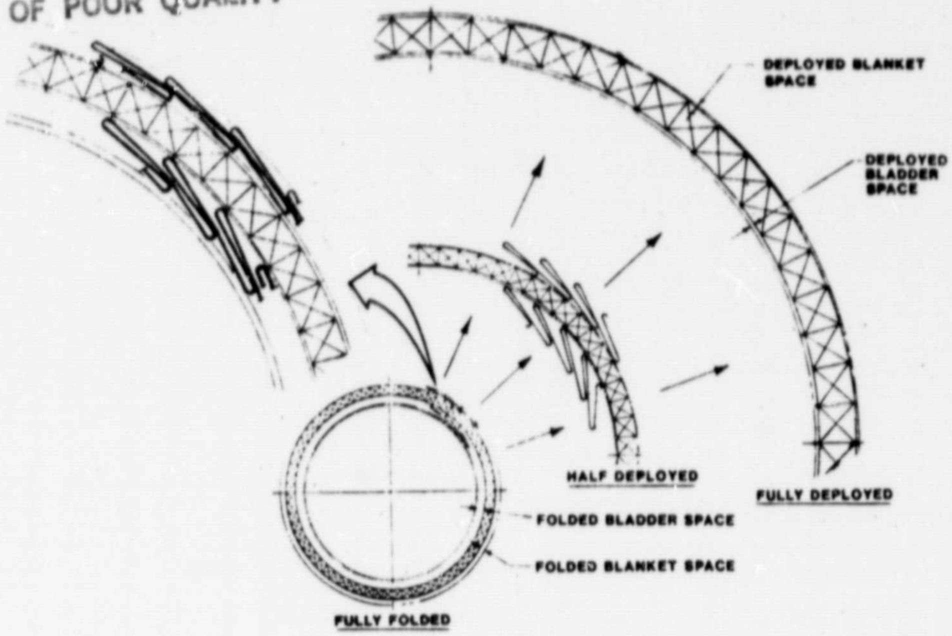

FIGURE 52

PERIFERAL EXTERNAL BLANKET AND BLADDER FOLDING/DEPLOYING

row of A nodes. The blanket is pushed fully open by the deploying truss cylinder, while the bladder must be fully opened by low gas pressure. Remaining attachments to the structure are then made by IVA and EVA.

A scheme for folding the thermal/meteoroid blanket end discs is illustrated in Figure 53. The radially pleated blanket is attached to the truss at the outer A nodes. The balance of the pleated blanket is then rolled

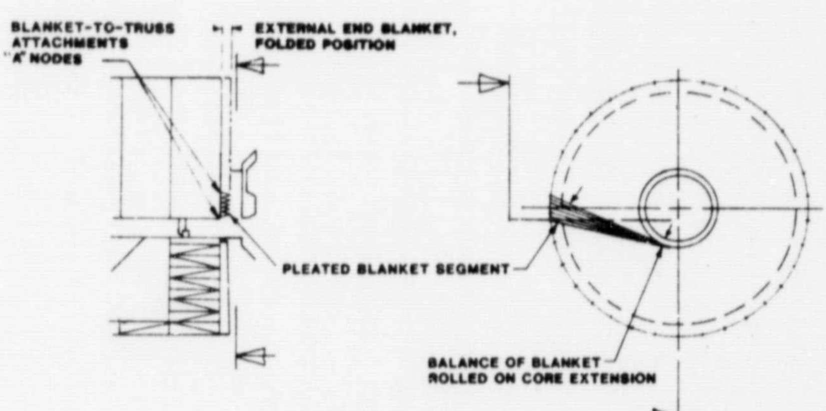

FIGURE 53

EXTERNAL BLANKET FOLDING - END BLANKETS

around the core extension as the outside diameter is reduced during folding. As the truss structure deploys the pleated end blankets automatically unwrap and expand to cover the end structure.

4.0 CONCEPTUAL DESIGN

The selected habitat and hangar concepts are described in this section with information provided on the operational aspects of delivery and buildup as well as packaging information and information on the detailed structural characteristics. The section is closed with a summary of supporting analyses performed to verify the concepts.

4.1 HABITAT CONCEPTUAL DESIGN

4.1.1 Concept Description for Delivery and Safety

Figure 54 pictures the concept for initial delivery and buildup of the deployable habitat. It is assumed that a Space Station is already in orbit. A Space Shuttle carrying the habitat module and outfitted with a docking module rendezvous with a Space Station and docks to it. Subsequent to

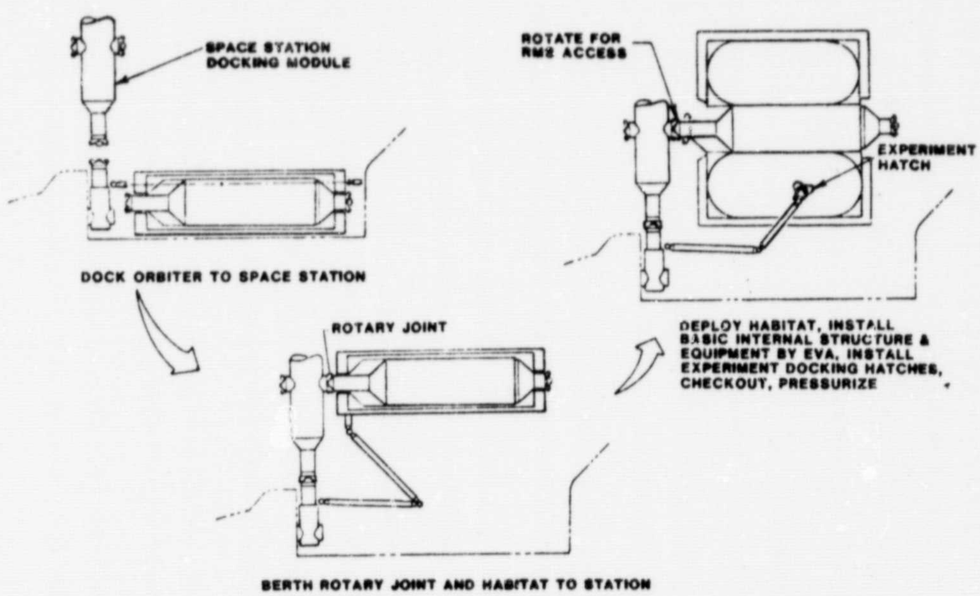

FIGURE 54

INITIAL DELIVERY AND BUILDUP OF DEPLOYABLE HABITAT

docking, using the RMS, a rotary joint interface is berthed to one of the docking ports on the Space Station. Following this the habitat is berthed to the other face of the rotary joint, again using the RMS. The purpose of the rotary joint is to allow the deployable habitat to be positioned within reach of the RMS for addition of external subsystems and elements. Once the berthing of the habitat module to the Space Station has been accomplished, it is deployed. This deployment is accomplished by a combination of the structural deployment system releasing its energy and light pressurization of the annular bladder in the habitat. To provide for this light pressurization, openings in the habitat for hatches are covered with a temporary seal. After the initial deployment is accomplished, crewmen enter the bladder area and complete the interfacing of the bladder with the truss structure by IVA. Next, the docking hatches are removed from the cargo bay and installed in the four external locations using the RMS. At the same time an IVA crewman completes the seal between the hatch and bladder on the inside of the deployable volume. The system is then checked for pressure integrity. Following this the subsystems contained in the core module are activated and checked out. At this point the securing of external items such as the insulation blanket is completed. Next, the floor structures and airlocks are installed. The initial delivery is now terminated by undocking from the Space Station and returning the Shuttle to earth. The second Shuttle delivery is pictured in Figure 55. The Orbiter carries up a cargo module which is pressurized and about 4.3m (14 ft) in diameter by 15.2m (50 ft) long with an

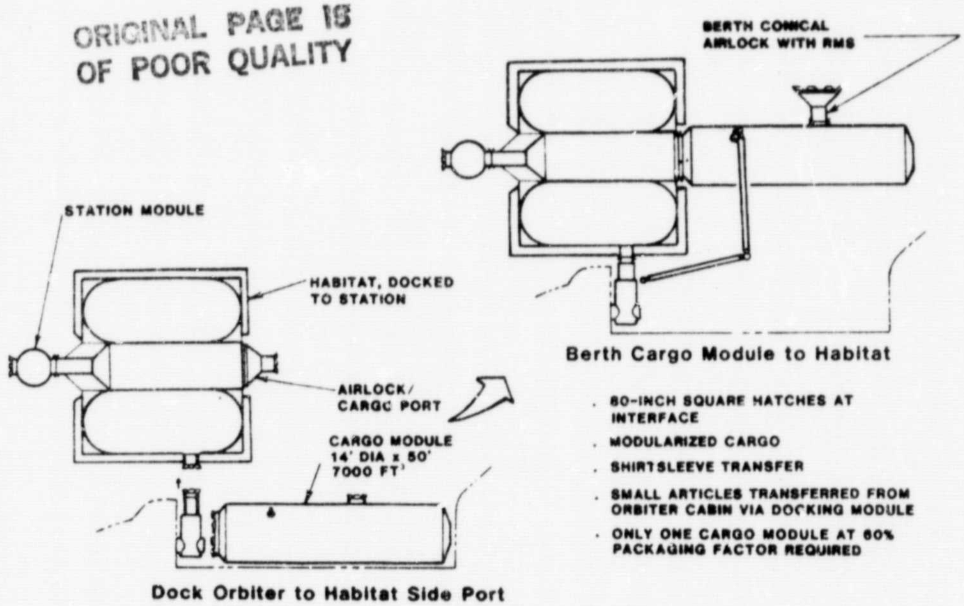

FIGURE 55

SUBSEQUENT DELIVERIES AND BUILDUP OF DEPLOYABLE HABITAT

internal volume of about 200 m^3 (7000 ft^3). A docking module is also installed in the Shuttle. After rendezvous with the Space Station, the

Shuttle docks into one of the experiment ports on the side of the habitat module. This provides access to the conical airlock cargo port on the aft end of the deployable volume. Using the RMS, this airlock is undocked from the habitat module and berthed onto the berthing adapter on top of the cargo module. The purpose of storing the conical airlock on the cargo module is two-fold: 1) it provides a convenient location and 2) it provides an emergency egress route for crewmen in the cargo module in the event of an accident during assembly and unloading. Again using the RMS, the cargo module is berthed onto the end of the core module of the habitat. Hatches in both the cargo module and the core module are approximately 2m (80 in) square to facilitate transfer of modularized cargo. A pressurized environment is provided to allow shirtsleeve operations. In addition, small articles which are stored in the Orbiter cabin can be transferred through the docking tunnel. An analysis of the equipment to be loaded into the deployable habitat indicates that one cargo module loaded at about a 50% volume packing factor can carry the entire internal equipment in one load. External equipment is also installed on the habitat module at this time, depending on available space in the Shuttle cargo bay for transport. Major items that require installation include tankage for nitrogen and oxygen which would be placed inside the deployed truss structure area on the end caps, radiator panels, and externally mounted subsystem components such as those for the freon coolant loop The tankage mentioned is in addition to a smaller quantity of high pressure gases stored on the exterior of the core module on the Space Station end. Because of the low density packing required in the cargo module, it may be desirable to reduce its diameter and provide more space for transport of radiator panels and subsystem items. The types of radiators that could be applied would be body mounted radiators using the constructable radiator concept currently under development by NASA-JSC. This would entail installation of fluid manifolds at either end of the deployed habitat cylinder and then mating long heat pipe panels into the fluid manifolds using a contact heat exchanger interface similar to that also being developed with the constructable radiators. Once the items are all transfered from the Shuttle to the habitat, the cargo module is repositioned and loaded in the Shuttle cargo bay and the conical airlock is reberthed to the core module. The Shuttle then undocks and returns to earth.

Further studies are required to determine if it is possible to carry all the external and internal equipment in the second Shuttle flight. Depending on orbit selection, launch weight may exceed Shuttle capabilities. Although no system weight studies were made, it is likely that the habitat weight would be in the 54,500 kg (120,000 lb) range of the ISS. If the delivery weight could be evenly divided between flights, and an allowance of 1360 kg (3000 lb) were made for the docking module, the combined weight of 28,600 kg (63,000 lb) is marginal in any case. It may be that a third flight is necessary to completely outfit the habitat module.

Important elements of the large habitat module are its safety features, illustrated in Figure 56. One element is compartmentation into two separate pressurizable volumes. The second is dual egress at several levels;

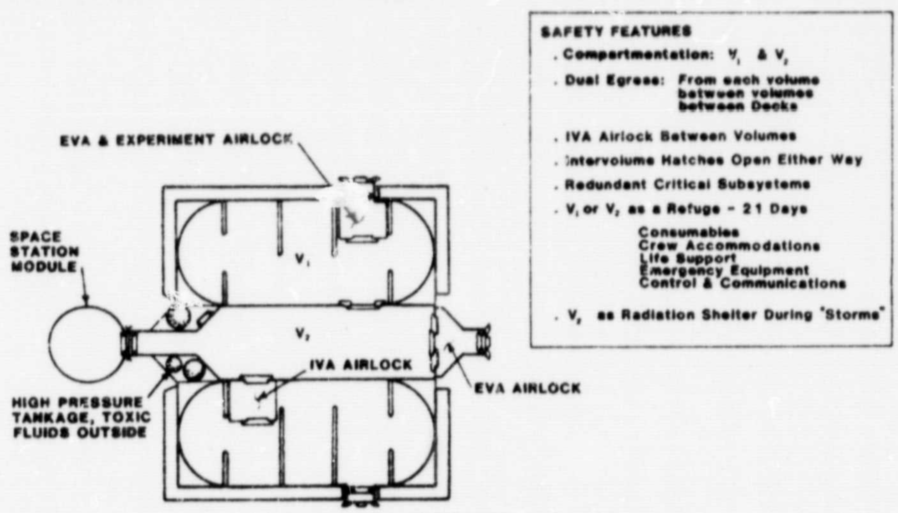

FIGURE 56

OVERVIEW OF DEPLOYABLE HABITAT SAFETY CONCEPT

between decks, between volumes, and from each volume. In order to enable repairs to be made on orbit, an IVA airlock between volumes is provided. The larger volume, V_1, is the main living and experiment area. The second core volume, V_2, serves the purpose of a refuge and is outfitted for twenty-one days with consumables, crew accommodations, control and communications, and emergency equipment. This smaller volume, V_2, can also serve as a radiation shelter during storms. Another safety feature is the provision of redundant critical subsystems. This applies both in component redundancy in the major subsystems for V_1 and V_2, and in the total redundancy in subsystems between V_1 and V_2, providing V_2 with a limited redundant operational capability.

4.1.2 Allocation of Functions

The general arrangement of the habitat is illustrated in Figure 57. The core module, pictured in cross-section, shows a large entrance door at the airlock end and a second large door separating Volume 1 and Volume 2.

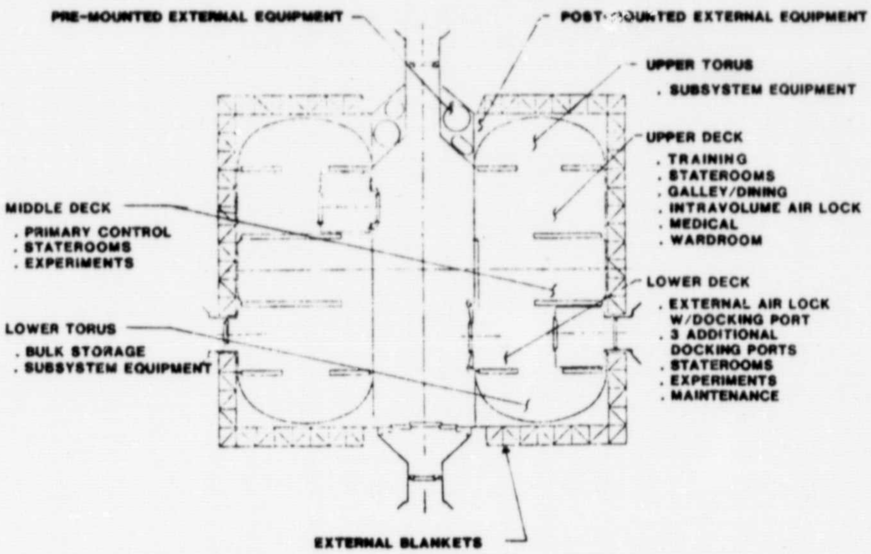

FIGURE 57

HABITAT GENERAL ARRANGEMENT

These are the 2m (80 inch) square hatches for transport of modularized equipment. The arrangement of functions between the various elements of the main volume, V_1, is shown. Subsystem equipment and bulk storage is provided in the half-torous volumes at either end of the bladder. The three floors have functions allocated as indicated on the figure. These were derived from the allocation of functions between four floors in the Ref. 10 Integral Space Station study. That reference was also used to define the complement of equipment and the volumes involved. Figure 58 shows the deck arrangements for this equipment, which are representative but not optimized. Some of the features of the arrangements include four docking hatches on the lower deck, one served by an airlock which provides both emergency EVA and also experiment functions. Passageways are provided on either side of the core to allow interdeck transport in the event of emergency, as well as convenience. A

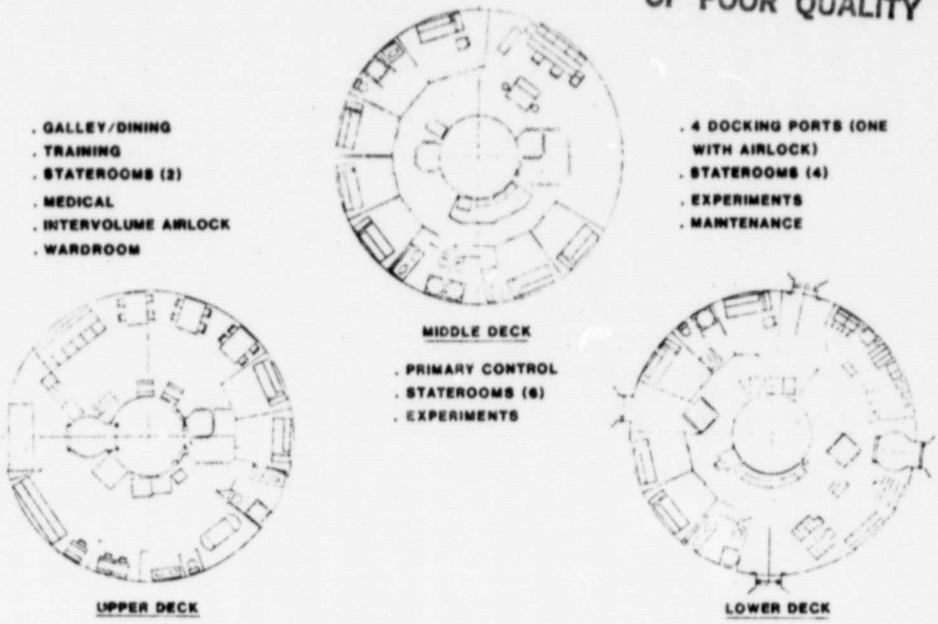

FIGURE 58

MAIN DECK ARRANGEMENTS

larger opening with a removable section is provided on each floor to allow relocation of large equipment as mission evolution proceeds. Staterooms and facilities are provided for a crew complement of twelve.

The core module, Volume V_2, functions are tabulated in Table 10. It provides a rigid backbone with preassembled subsystems for startup and

TABLE 10

CORE MODULE CONCEPT FOR HABITAT SECONDARY VOLUME V_2

Provides Rigid Backbone
- launch packaging and pallet interface
- main structural member on-orbit

Pre-Assembled Subsystems
- startup operations from V_1
- backup control center
- backup subsystems for limited operation

Central Utilities
- redundant utilities trunk tunnels
- annular plenum for V_1 ECS ducting

Refuge Volume
- 21-day provisions for 12 man crew
- storm shelter
- personal equipment for emergency rescue
- EVA/IVA capability
- limited repair capability

Launch Stowage To Support V_1 Deployment/Erection
- floors and ceilings
- ducting
- electrical and fluid line bundles
- airlock

backup, redundant utility trunk tunnels, and a convenient annular plenum for environmental control system ducting for the main volume, V_1. In addition, it provides a refuge volume with limited repair capability and serves a second purpose as a stowage volume during deployment and assembly. A layout of V_2, approximately to scale, is given in Figure 59. Since it must serve as a refuge it is important to provide adequate free volume for 12 men. The layout

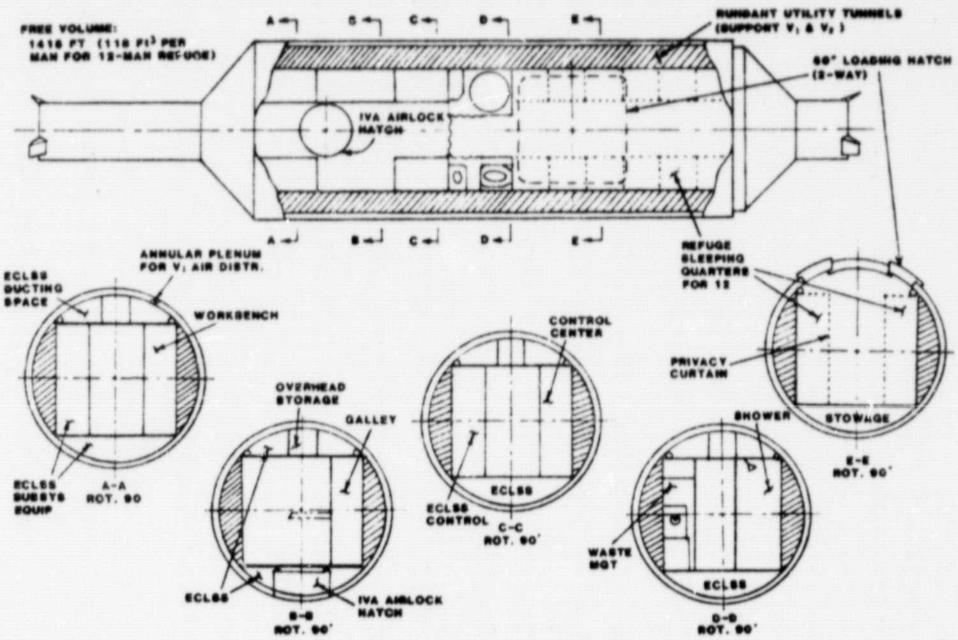

FIGURE 59

LAYOUT OF CORE MODULE V_2 SHOWING PRE-INSTALLED SUBSYSTEMS AND FURNISHINGS

was based on the Celentano free volume criteria of a minimum of 3.26 m^3 (115 cu.ft.) per man for useful capability for a limited time period. The plan view at the top of the figure shows the two redundant utility tunnels containing the utilities to support both V_1 and V_2. It also indicates the annular area at the outside of the core providing a plenum for V_1 air distribution. During normal operation the hatches between V_1 and V_2 are open and the air is circulated between both. Valving is provided to seal off the ducting in case of an emergency. A separate limited duration air revitalization system is provided to support V_2 and startup/emergency operations in V_1. The sleeping quarters for 12 consist of sleeping bags and privacy curtains that can be retracted to provide additional isle space. Hygiene areas are shown as are the control areas, galley, workbench, and environmental control/life support system dedicated areas. This layout provides a total free volume (with the privacy curtains retracted) of about 40.1 m^3 (1415 cu.ft.), or about 3.34 m^3 (118 cu.ft.) per man for a twelve man refuge chamber.

4.1.3 Structural Design and Assembly

Using the selected Biaxial Double Fold truss, geometric studies were conducted while varying the number of cells in the truss hoop from 28 to 80. Five geometric combinations of hoop and end plate truss cell numbers and sizes which can be folded and deployed while connected together at the A and B nodes were determined. Figure 60 shows the 68 cell hoop selected for the habitat deployable truss structural configuration. There are 212 cells in the end plates. This configuration was selected as the best compromise between deployed strength and folded compaction.

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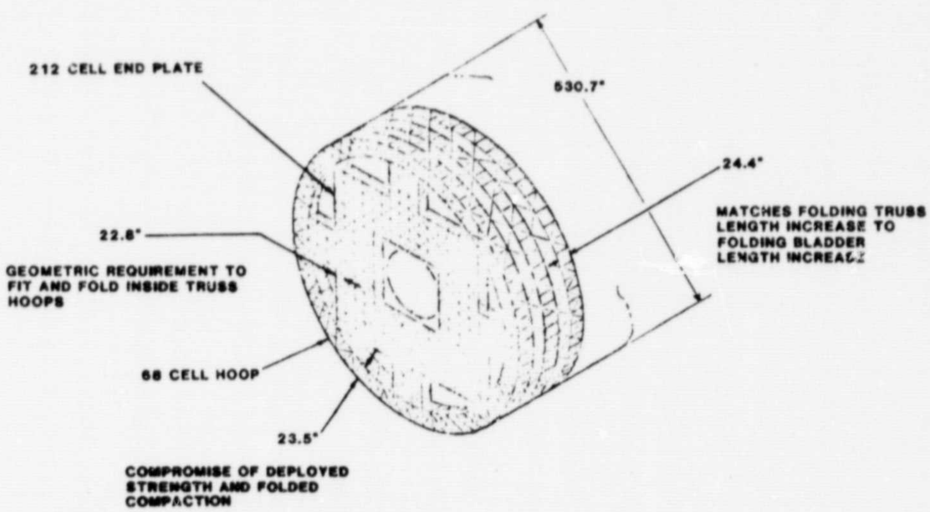

FIGURE 60

HABITAT DEPLOYABLE TRUSS STRUCTURAL CONFIGRATION

Figure 61 shows the structural concept selected for the deployable deck design for the habitat module. The Biaxial Double Fold truss concept was again used, and each deck was subdivided into four pie-shaped sections. The four sections are cut at 45^o to the square cells because nodes can be split at 45^o without any duplicate parts in parallel when sections are joined to complete the truss. The floors are attached to both the core module and the truss cylinder, which are already connected together by torsion in the bladder

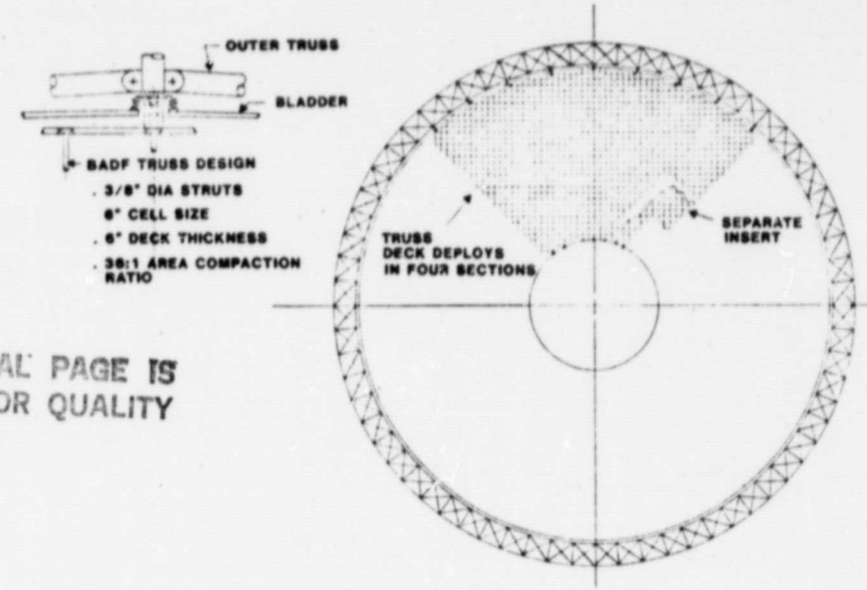

FIGURE 61

DEPLOYABLE DECK DESIGN FOR HABITAT MODULE

and by external connectors at each end. Therefore, no surface tension diagonals are used to provide floor truss shear stiffness, which would be a redundant load path and could possibly cause problems in floor support alignment due to tolerances. The floor truss will provide a 15.2 cm (6 inch) grid pattern of nodes with an attach socket in each node. Mounting equipment at any location is possible by orienting attachment patterns in the base to match the floor gird. Floor truss thickness is also 15.2 cm (6 inch), and the area compaction ratio is about 36:1. A flooring mesh, as shown in Figure 62, covers the 15.2 cm space between the truss struts to provide a defined surface

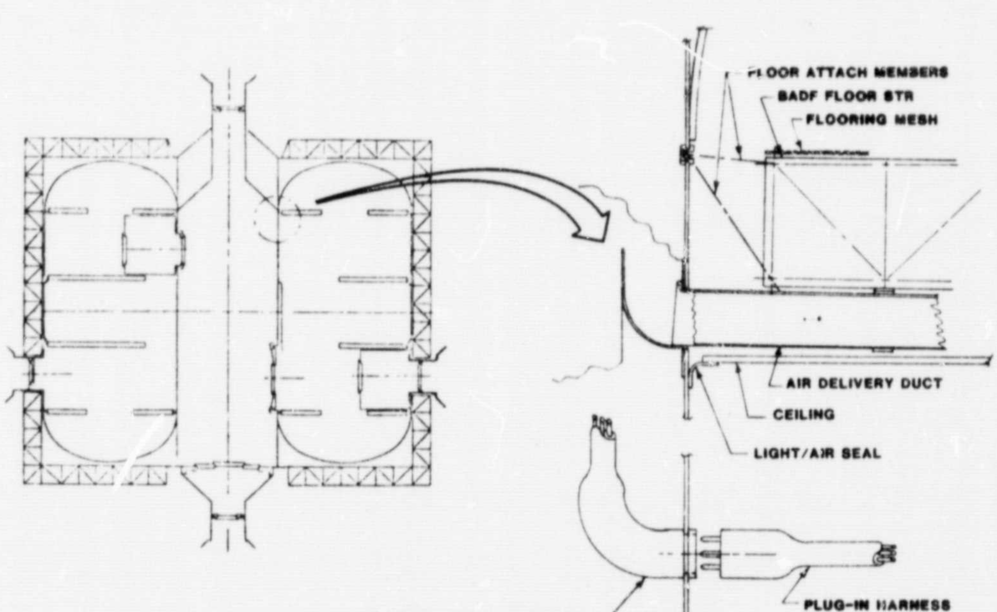

FIGURE 62

FLOOR/UTILITY INSTALLATIONS FOR DEPLOYABLE HABITAT and to allow boot interface. The opposite side of the floor truss supports utilities harnesses and conduits, air ducts, and light fixtures for the compartment below. These are covered with a false ceiling to form a light/air/sound/privacy seal between compartments. The floor truss structure is attached to the central core at one point and then is expanded to its full diameter using spring energy and a simple restraint mechanism. Structural connections are then made through the indicated penetration in the bladder to the outer truss, and connections to the core module are completed The 2m (80 inch) square opening for transport of equipment is provided by leaving out a section of several cells from two of the four pie shaped truss sections. To minimize the wasted space during subsequent operation, an insert with a smaller opening is added.

The concept for installation of the four docking ports into the outside diameter of the deployable structure is illustrated in Figure 63. The docking port is inserted through the truss structure and interfaces with the bladder. In order that the installation may be accomplished using the RMS, an

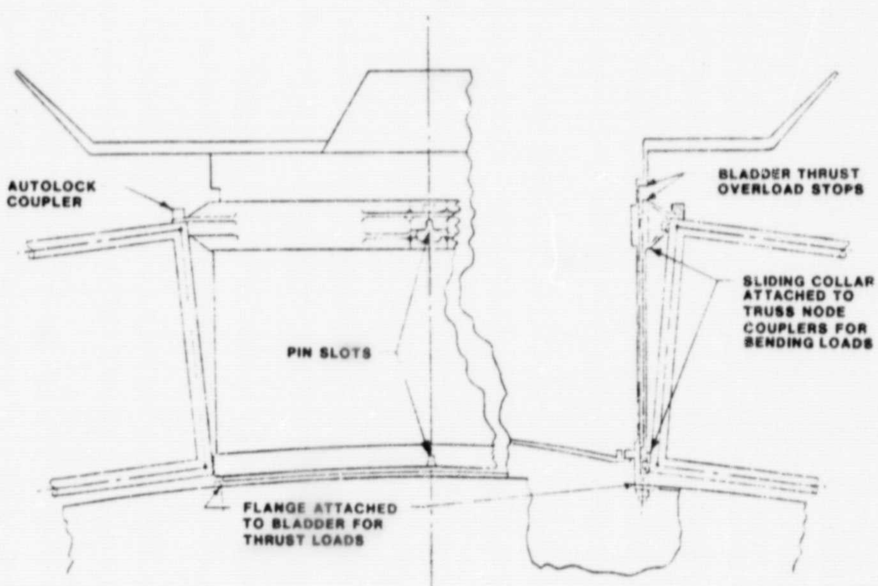

FIGURE 63

DOCKING PORT INSTALLATION FOR DEPLOYABLE HABITAT

Autolock coupler is provided on outer nodes of the truss to interface with the docking port structure. Similarly, pin slots are provided to interface

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between the docking structure and the truss structure at the inside diameter of the truss. These connections are made without EVA assistance. The interface between the bladder and the flange of the docking structure requires IVA. A temporary cover and seal is removed from the opening in the bladder by the IVA astronauts and the bladder is bolted to the flange. A telescoping sliding capability is provided in a collar attached to the truss node couplers. The primary docking thrust load is taken by the bladder. Then additional sliding causes the telescoping section to bottom and the excess thrust is shared by both the truss structure and the bladder after the overload stops are contacted. The primary bending loads on the docking port are taken by the truss structure through the sliding collar due to the low bending stiffness in the bladder interface area.

Once the docking hatches are installed and pressure integrity of the bladder is insured, additional work inside the volume can be accomplished in a shirtsleeve environment. Figure 64 illustrates the sequence of accomplishing floor and airlock installation. On the left side of the figure the stowage positions are indicated where the folded floor structure is stored

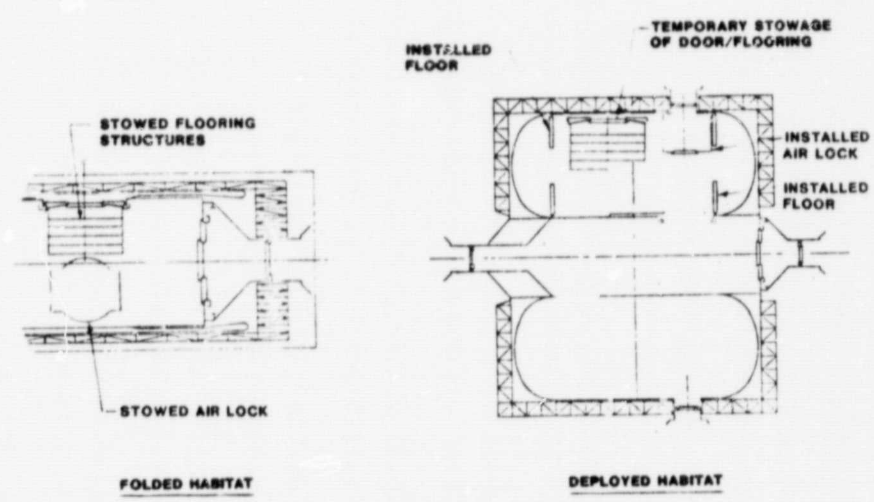

FIGURE 64

AIR LOCK/FLOOR INSTL - AIR LOCK-EVA FLOOR-SHIRTSLEEVE

on the back of the 2m (80 inch) square intervolume door. The airlock is stored for launch in volume V_2. First, the door is removed from its sliding rail and positioned in V_1. The upper and lower torous decks are next installed. Following this the airlock is transported from V_2 into V_1 and installed on one of the hatches. The floor installation is then completed and the intervolume door is replaced. Not shown in Figure 64 is the IVA airlock which is also carried on the first Shuttle flight and installed at the same time the EVA airlock is installed. The next step in buildup is to install the remainder of the floor and utilities runs in V_1. The flooring mesh is unrolled and placed on the floor. The air delivery duct and the electrical and fluid harnesses are then removed from V_2 and installed. The utilities are routed to predetermined locations and are pre-sized to the right dimensions upon delivery.

4.2 HANGAR CONCEPTUAL DESIGN

Three OTV configurations were presented in Figure 43 of Section 3.1: Centaur G; the Air Force version of Centaur G, Centaur G'; the longer NASA version; and a reusable OTV concept derived by Boeing under NASA Contract NAS1-16088 and used in the Reference 8 Space Operations Center Study. The two Centaur vehicles provide characteristics representative of a near term ground based cryogenic OTV, while the Boeing concept is representative of a potential unmanned space-based cryogenic reusable OTV. Other potential users of an OTV hangar include solid propellant upper stages and a future manned OTV (Ref. 8). The manned OTV would be considerably larger, estimated in Ref. 8 to be about 25 m (81 ft) long by 4.5 m (15 ft) diameter with a mass of 54,000 kg (130,000 lbs). With this additional size, and the considerations associated with manned operations, the OTV hangar physical characteristics would necessarily be impacted from those required to accommodate the Figure 43 vehicles. It is expected, however, that the basic concept derived herein would remain applicable. Another vehicle which will play a role in OTV hangar operations is the TMS, both as a maneuvering aid for the OTV and payloads relative to the hangar, and as an orbital transfer vehicle itself, acquiring and delivering satellites when servicing operations are performed.

Potential uses for the OTV hangar have been enumerated in Refs. 2, 8, and 9. For non-reusable OTVs the hangar may find use in final checkout of the OTV before orbital transfer from the Space Station, and also for payloads that are too large to be delivered to orbit with the OTV in a single Shuttle mission. In that situation the hangar may be used for payload/OTV mating operations, and it may also be used as a parking facility for the OTV for a period of a few weeks while the payload is delivered by another Shuttle flight. It is also possible that on-orbit fueling of a non-reusable OTV in the hangar would be needed for future missions if a space-based propellant depot were available in conjunction with a Space Station. In the case of space-based reusable OTV vehicles, refueling, maintenance, and payload changeout could take place in the hangar.

While the present study presumes that a requirement for an OTV hangar exists, some prior studies have addressed the question of the justification of a hangar based on the benefits that might be derived. Table 11 summarizes some of the potential benefits of using an OTV hangar. One of the main benefits resulting from hangar usage is the fact that an EVA spacesuit will not be required with extravehicular visor assembly and full thermal insulation. In order to perform IVA it will only be necessary to have a pressure garment and life support system for the crewman (if the hangar is not pressurized) rather than the full insulation complement. This would result in much better visibility and dexterity. Other obvious benefits are the provision of a benign environment to work in, which benefits both the OTV and possible payloads as well as the crew. Since allowable crew exposure to the radiation environment is limited, the radiation shielding the hangar provides will avoid shortening allowed tenure of crewmen on orbit. Another advantage is that the hangar provides containment for items that may be dropped, and facilitates management of refuge or expelled matter from the vehicle. If the hangar is pressurized there are further benefits that accure. Because the crew is operating in a pressurized environment no suit will be required and a greatly improved mobility and dextrity will result. In addition, the lost time due to pre-breathing will be eliminated, as will be the time required to don the suits. A distinct disadvantage of operating the OTV hangar pressurized is the fact that depressurization during egress and ingress of the vehicle will be required. With a volume of 850 m^3 (30,000 ft^3), such as indicated in our conceptual design, about 20 to 50 kW will be required to pump down the hangar over a period of about 24 hours. While this penalty appears large, it may be possible to avoid any real penalty through scheduling. Another potential disadvantage of performing refueling, servicing and maintenance operations in a pressurized environment is the potential hazard due to spillage or leakage of dangerous fluids. Additional work will have to be carried out to determine if a suitable containment concept can be implemented to allow this to be safety done. Another altnerative mentioned in

TABLE 11

DEPLOYABLE HANGAR GUIDELINES AND PURPOSE

HANGAR BENEFITS - GENERAL

Provides benign thermal/radiation/meteoroid/debris environments

- avoids compromise to crew work shifts and tenure
- protects OTV and mating spacecraft (including extended parking)

Provides improved visibility

- 360^{o} lighting
- avoids solar protective visor

Improves mobility and dexterity

- no glove or suit thermal insulation required
- untethered translation acceptable

Provides containment

- avoids need for tether on parts and tools
- facilitates management of refuse and expelled matter

BENEFITS OF PRESSURIZATION

Greatly improves crew mobility and dexterity

- no pressure suite

No time lost prebreathing (as applicable) or donning suits (but hangar pumpdown time is added to move OTV in or out)

C-2

Ref. 8 is that of pressurizing a hangar with an inert atmosphere which would provide most of the advantages previously listed.

4.2.1 Operational Concept

Figure 65 illustrates the basic approach for OTV ingress and egress. Three important characteristics of that system are shown in the figure. First, the circular, cylindrical hangar pivots open like a clamshell providing a large opening for the OTV. Second, internal hard structure in the

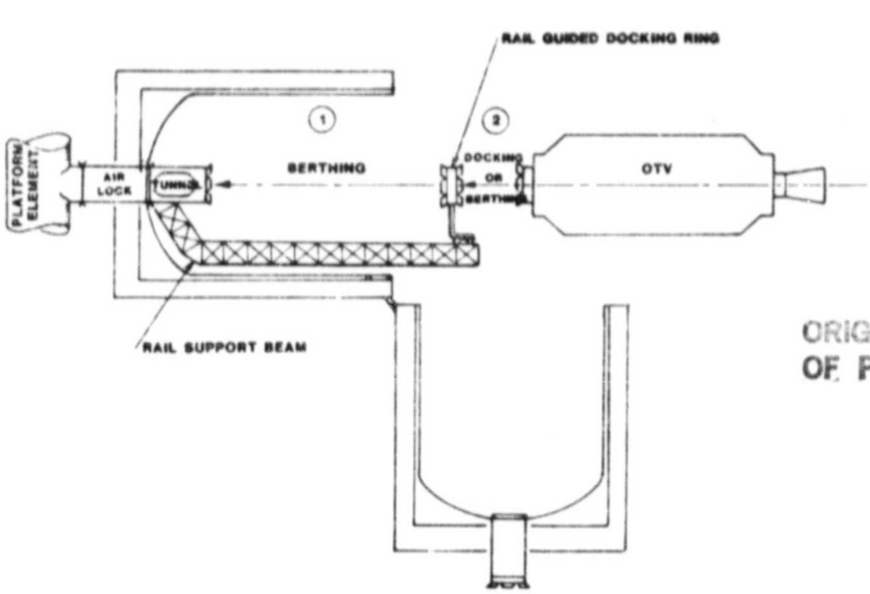

FIGURE 65

CONCEPT FOR OTV INGRESS/EGRESS

hangar provides a firm mounting for the OTV and consists of a central core tunnel for the docking adapter and a deployed truss beam which incorporates guide rails. The third element is the docking interface, illustrated here as a rail guided docking ring. It is shown in use with the reusable OTV, which has a docking ring on the forward end. The OTV may either be brought in the proximity of the hangar and then flown into the docking ring or berthed into the docking ring using the RMS. After docking is accomplished the rail guided docking ring is translated with the OTV into the hangar and hard docked into the tunnel. As appropriate, additional supports may be made by the dolly such as an extension of the dolly under the OTV with arms to pick up the trunnion mounts already on the OTV for Shuttle interface. The rail guided docking ring is mission specific hardware and would be suitable only for the situation indicated where the OTV has a docking adapter on the front. Other OTV vehicles such as the Centaur have a docking cradle on the aft end. The adapter ring would then be configured to interface the OTV with a structure similar to the cradle which would, in turn, dock into the hangar tunnel for firm support. For suitations where payload mating with the front of the OTV is desired, the docking ring would have a configuration which interfaces directly with the trunnions on the OTV or with an adapter situated on the aft end of the OTV allowing free space for payload mating. By extending the rail support beam further from the base of the hangar, through incorporation of an extension mechanism, other options would become available for interfacing with the OTV. For instance, the rail guided docking ring in Figure 65, could be swiveled on the vertical post supporting it. This would allow rotation of the OTV from a position in front of the docking ring to a position behind the docking ring before it is translated into the hangar. It could then be mated with a dolly carrying trunnion supports and backed into the hangar allowing free space for work on the front end of the OTV. Once the OTV has been successfully docked and secured to the hangar structure, the hangar clam shell would be closed and the system would be pressurized. This would allow entrance of the crew from the Space Station platform element through the passageway in the airlock and out through the door shown in the tunnel. If the hangar were unpressurized the route would be the same but the airlock would be used to go from the pressurized platform to the unpressurized hangar area.

4.2.2 Design and Assembly

Additional details defining the conceptual design configuration of the deployed OTV hangar are given in Figure 66. The reusable OTV is shown in

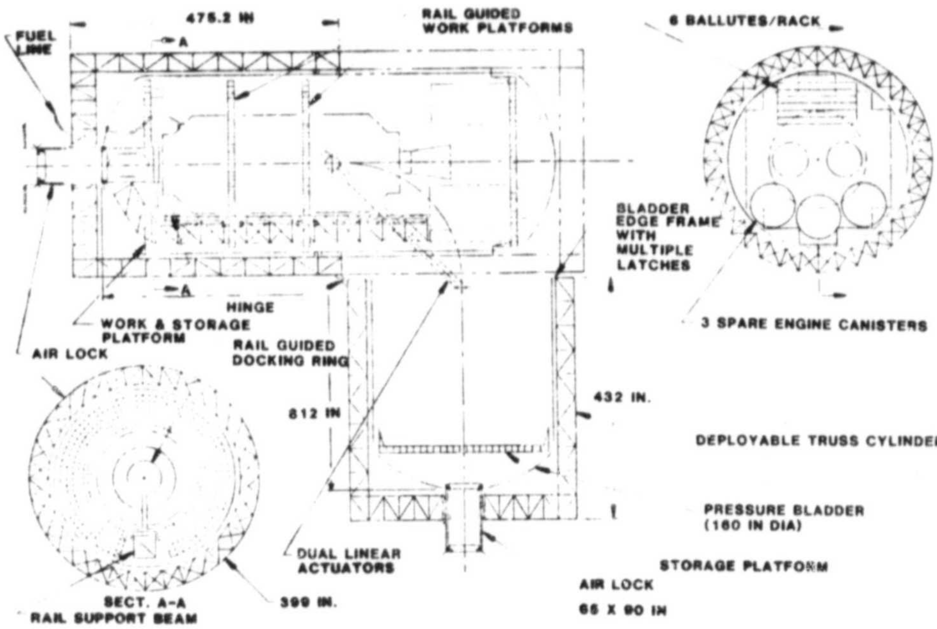

FIGURE 66

DEPLOYED OTV HANGAR CONFIGURATION

the hangar undergoing a refueling operation. The central load carrying structure is the 1.65 m (5.4 ft) diameter airlock which is mated to the 1.27 m (4.2 ft) diameter tunnel which, in turn, mates and supports the OTV through the docking ring. The deployed rail support beam is also part of the main structure. It provides a guideway for the movable work platforms as well as a strongback mounting structure for the dolly which interfaces with the OTV and the docking ring. The deployed truss structure interfaces with the airlock to provide the structural attachment on the forward end. It is hinged to the aft half which is opened and closed using dual actuators. A second airlock is afixed to the aft end of the hangar to provide an alternate egress route during pressurized operation should an emergency block egress through the forward end of the hangar. The bladder is attached to the separate hangar halves during stowage and is deployed with the hangar. EVA is required to install the bladder edge frame (which supports the seal between the halves) and the seals between the airlocks and the bladder. The external thermal/meteoroid blanket is also folded and deployed with the hangar but is not shown in the figure. The work platforms are also BADF deployable truss structure as are the storage platforms at the forward and aft ends of the hangar. Also shown in the figure are stored spare engines in canisters and other small equipment items necessary for servicing the reusable OTV. While space is adequate inside the hangar for the reusable OTV and spares shown, if a payload were to be mounted to the OTV additional space could be provided possibly by external storage of spares or by lengthening the hangar. While sufficient interior space exists for mating numerous payloads to the shorter Centaur OTV versions, the extra space would be required for the reusable OTV. The length of the hangar is determined by the Shuttle cargo bay length. The forward half of the design shown is the maximum length that can be stored in the cargo bay. The aft half could be lengthened to the same as the forward half providing an overall length increase of about 1m. Should a still longer hangar be required, a second Shuttle flight could be used to transport intermediate sections of about 12m in length each.

Figure 67 gives additional detail on the OTV hangar packaging configuration. The forward half of the hangar is shown. The configuration for the aft half would be similar. A central core cylinder forms the structural strong back for supporting the retracted truss in the Shuttle cargo

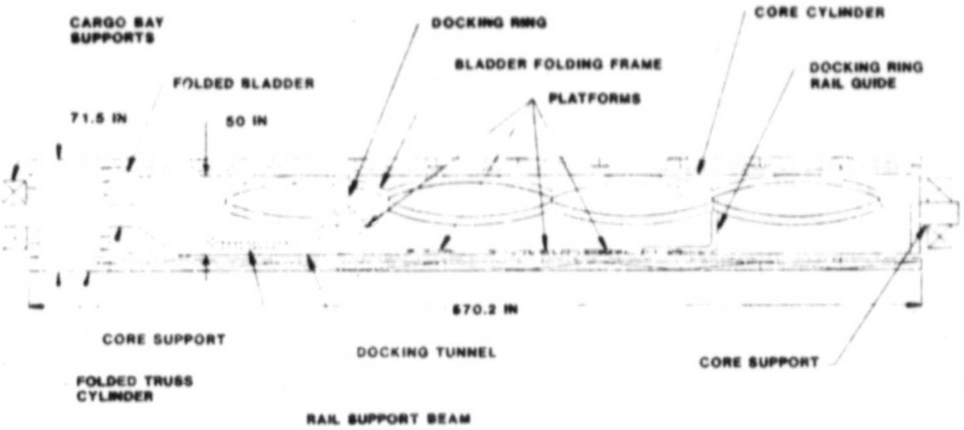

FIGURE 67

OTV HANGAR PACKAGING CONFIGURATION FOR LAUNCH

bay and for containing the various equipment items necessary for outfitting the structure. The docking tunnel forms part of this core cylinder. The two airlocks are stored parallel to the folded truss as is the other half of the deployable structure. Figure 68 shows the truss arrangement selected for the hangar constructural configuration. The end plate consists of 80 cells and

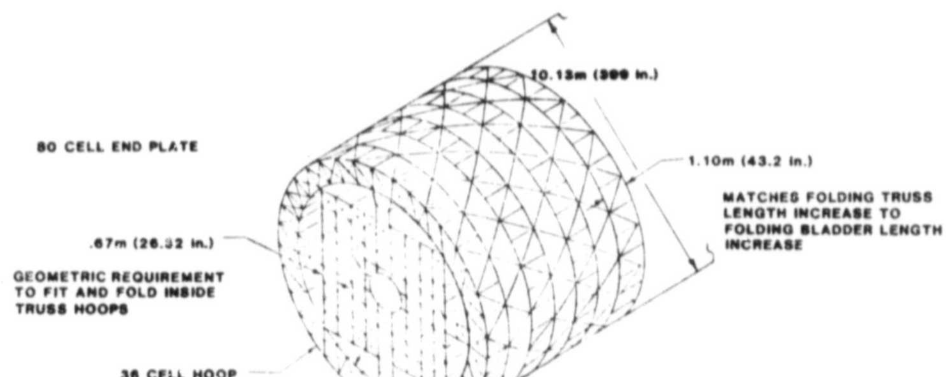

FIGURE 68

HANGAR DEPLOYABLE TRUSS STRUCTURAL CONFIGURATION

the hoop of 36 cells, selected as the best compromise between deployed strength and folded compaction. The non-cubical dimensions of the cells were chosen to match the bladder length change during folding. At the core of the truss short transition structure is required to interface with the airlock. The detachable circular hoop bladder edge frame is shown in Figure 69 in both the folded and deployed configurations. The stowage location is given in

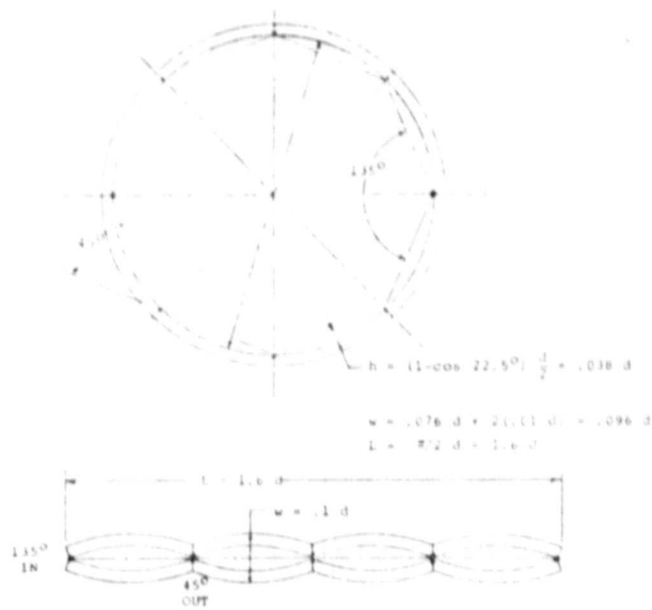

FIGURE 69

DETACHABLE BLADDER EDGE FOLDING FRAME

Figure 67. A crossecctional illustration is given in Figure 70 showing the attachment of the bladder to the frames and showing the seal arrangement.

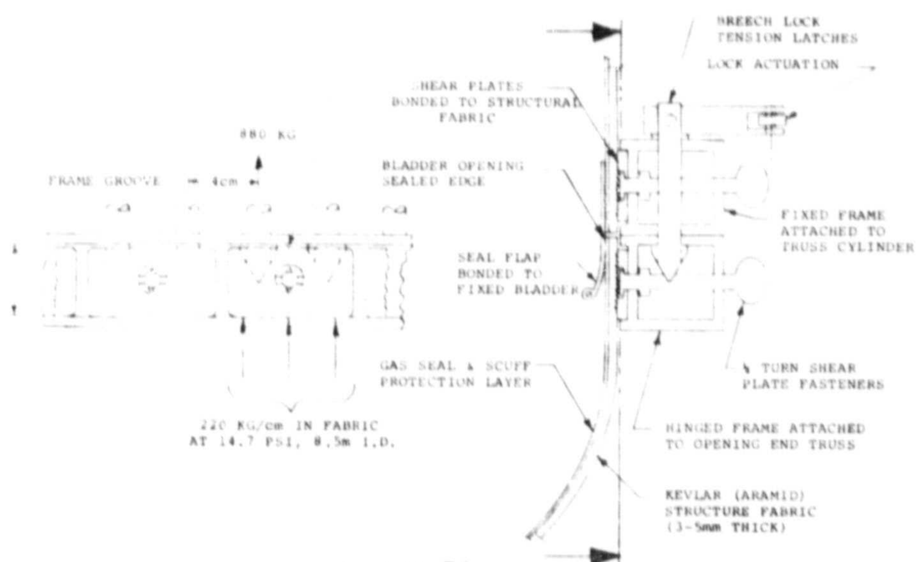

FIGURE 70

DETACHABLE BLADDER EDGE FOLDING FRAME

Installation of the frame onto the deployed structure utilizes both RMS and EVA operations. The entire sequence of operations required for deploying and building up the hangar is summarized in Table 12.

TABLE 12

OTV DEPLOYABLE HANGAR BUILDUP

1. Dock Orbiter to Platform Element
2. Berth Air Lock to Platform Element (RMS)
3. Deploy First Half of Hangar Module, Remove Forward Core Support, and Install Tunnel End on Air Lock (RMS & EVA)
4. Deploy Second Half of Hangar Module ,Connect by Hinge and Dual Actuators to First Half (RMS & EVA)
5. Remove Core Support and Install Air Lock to Second Half (RMS & EVA)
6. Remove Remaining Core Supports and Install Bladder Edge Frames (RMS & EVA)
7. Close Hangar and Complete Bladder Attachments, Pressurize Hangar and Check Seals (EVA & RMS)
8. Remove Deployable Decks and Rail Support Beam from Core Cylinder and Tunnel and Install (Shirtsleeves)
9. Pump Down Bladder, Open Hangar to Remove Core Cylinders and Install Spare Equipment and Tools (EVA & RMS)
10. Hangar is Complete and Ready for Docking OTV

4.3 DEPLOYABLE VOLUMES ANALYSES

Several preliminary analyses were performed in support of the deployable volume concept evolution in order to assure feasibility, to assess capability to meet mission requirements, and to provide design definition. The following four subsections summarize these analyses.

4.3.1 Structural and Dynamic Analyses

Sizing of the main truss structure, habitat core module structure, bladder and thermal/meteoroid blanket were all carried out based on all mission requirements considerations and evaluated for structural integrity. These are presented below with the exception of the thermal/meteoroid protection which is evaluated in the following Section 4.3.2. The overall deployable structure configuration has already been described for the habitat and hangar modules in Sections 4.1 and 4.2. The truss members for both cases were sized from packaging considerations to be 3.8 cm (1.5 in) diameter graphite/epoxy tubes. A tube wall gage of about 1mm (0.043 in) was selected with the material properties of GY70/934 graphite/epoxy assumed based on a balanced symmetric 8-ply layup with $\pm$ 10^{o} ply orientations. Those properties are the same as determined during Part 1 deployable linear truss studies. Its modulus is 260 GPa (37.7×10^{6} psi) and its ultimate compressive strength is 330 MPa (48×10^{3} psi). Density is 1.78 gm/cm^{3} (111 lbs/ft^{3}). The central core and tunnel/airlock material selection was 6061-T6 aluminum alloy. The gages selected were 0.32 cm (0.125 in) for the tunnel and airlock areas, and 0.16 cm (0.060 in) for the 11 ft diameter central module. Properties of this alloy are an ultimate compressive strength of about 310 MPa (45×10^{3} psi), a modulus of 72 GPa (10.5×10^{6} psi) and a density of 2.77 gm/cm^{3} (173 lb/ft^{3}).

The flexible material selected for the bladder structural layer was Kevlar 49 fabric. DuPont fabric style S-281, which is a plain weave material with a thickness of about 0.025 cm (0.010 in) and a weight per unit area of 0.017 gm/cm^{2} (0.035 lb/ft^{2}), was chosen. This fabric has a ultimate tensile strength of about 445 MPa (65×10^{3} psi). Structural considerations show that a total fabric thickness of about 0.76 cm (0.30 in) is required to support the pressure load with a safety factor of 5. This translates into 30 plys of the fabric for the habitat module. The hangar module requires approximately 0.51 cm (0.20 in) which is 20 plys. Other than the structural layer just described for the habitat and hangar modules, two other layers were included in the bladder. The inside layer, for atmospheric containment and a flame barrier, was taken from the Ref. 6 concept and consists of the following layup: an inner film of aluminum foil to serve as a flame barrier, an adhesive film, a laminate of Capran (Nylon film) and Nylon cloth, another adhesive film, a 0.18 cm (0.07 in.) thickness of closed cell ethelyene propylene terpolymer (EPT) foam, an adhesive film, and another Capran/Nylon cloth laminate. The outer most layer is another laminate of Capran film and Nylon cloth. The weights per unit area of the three layers are 0.0083 gm/cm^{2} (0.017 lb/ft^{2}) for the outer layer, 0.51 gm/cm^{2} (1.04 lb/ft^{2}) for the structural layer, and 0.085 gm/cm^{2} (0.173 lb/ft^{2}) for the inner atmospheric and flame barrier layer, giving a total weight per unit area of 0.60 gm/cm^{2} (1.23 lb/ft^{2}) for the total habitat bladder. Estimated overall thickness of the habitat bladder is 1.0 cm (0.393 in). The hangar bladder differed only in the structural layer, with a resulting overall weight per unit area of 0.43 gm/cm^{2} (0.88 lb/ft^{2}) and thickness of 0.74 cm (0.293 in).

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Table 13 summarizes the results of structural strength analyses conducted for the deployable volumes. Adequate margins of safety were found under launch loads, on orbit accelerations, and berthing. Docking loads were

TABLE 13

STRUCTURAL STRENGTH ANALYSIS FOR DEPLOYABLE VOLUMES

LAUNCH LOADS

. High margin of safety in stowed configuration under emergency landing (4.5-g max. acceleration)

ON-ORBIT ACCELERATION

. Max load due to 0.02-g results in high margin of safety in both truss structure and core module
. Critical point is at core docking adapter interface to Space Station

BERTHING

. Lowest margin of safety of 1.3 in truss/docking hatch interface in habitat module

DOCKING

. Under 3000 lb docking loads modest local beef up of deployable truss is required
. Docking hatches located in deployable truss limited to about 90,000 ft-lb moment with modest local beefup

found to be most critical. High stress values were determined in the vicinity of the docking adapters and the vicinity of the interface area with the tunnel and airlock sections. These high stresses occurred in the graphite epoxy structure. In the vicinity of the side docking adapters on the habitat module it was necessary to replace the tubular graphite/epoxy longerons with solid rods. This resulted in the capability to withstand a moment of up to 122,000 N.m (90,000 lb-ft) and to take the 1360 kg (3000 lb) load. In the case of the hangar it was also necessary to increase the crossectional area of the struts to about 4 cm ($0.62\ in^2$) both where the struts interface the end airlock docking adapter and where the struts interface the forward airlock and tunnel. With this modification the 1360 kg (3000 lb) docking force or the 162,700 N-m (120,000 lb-ft) moment could be accepted.

Table 14 summarizes results of stiffness analyses on deployable volumes. Spring rates in bending and extension are given in the table for both the habitat module and the hangar. The frequencies are also shown for the first modes, which in all cases were significantly higher than the 0.1 Hz minimum.

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TABLE 14

DEPLOYABLE VOLUMES - SPRING RATES AND FREQUENCIES

		HABITAT MODULE	HANGAR
EXTENSIONAL SPRING RATE (10' N/m)*		281	279
BENDING SPRING RATE (10' N/m)*		24.6	40
MASS EMPTY (KG)		4310	3200
MASS FULL (KG)		54,420	41,000
FUNDAMENTAL FREQUENCY: UNIFORMLY DISTRIBUTED LOAD DUE TO ACCELERATION (CANTILEVERED - BENDING)	f, EMPTY (HZ)	12	18
	f, FULL (HZ)	3.4	5.0
PERCENT OF DEFLECTION DUE TO BENDING SPRING RATE BY COMPONENT	AIRLOCK	98	15
	CORE	0.02	———
	BLADDER	1.64	65
	TRUSS	0.34	20

COMPONENT PROPERTIES:

AIRLOCK, CORE - E = 72.4 GPa, t = .32 cm (ALUMINUM)

BLADDER - E = 34.5 GPa, t = .76 cm (.61 cm ON HANGAR) (KEVLAR-49)

TRUSS - E = 260 GPa, LONGERON AREA = 1.3 cm^2 (GY70/934)

*CANTILEVERED FROM 1.5m DIA AIRLOCK SECTION

4.3.2 Thermal/Meteoroid/Debris Analyses

Thermal protection requirements for the deployable habitat and hangar are straightforward. The inner wall temperatures must be maintained below the pain threshold of about 45°C (113°F) and above the maximum cabin dew point temperature which is about 16°C (60°F). In addition, minimal heat gain and loss through the exterior wall to the contents of the deployed volume must be maintained. The approach chosen was to use an integral thermal/meteoroid blanket on the exterior of the structure. The current Spacelab layup was used as a representative blanket design without detailed analysis. Figure 71 illustrates the approach which requires the same level of protection as the NASA-MSFC SAMSP. The blanket thickness is about 0.5 cm (0.2 in) uncompressed, and the weight per unit area is about 0.05 gm/cm^2 (0.1 lb/ft^2).

The meteoroid protection approach was also similar to that used in the SAMSP design as illustrated in Figure 72. For the current deployable volume study that design was modified consistent with differences in deployable volume materials and the approach of mounting the blanket on the exterior of the truss structure which yielded a greater standoff distance.

REQUIREMENT:

- MAINTAIN MINIMAL HEAT GAIN/LOSS TO CONTENTS OF VOLUME
- MAINTAIN WALL TEMPERATURE BELOW PAIN THRESHOLD (45°C) AND ABOVE MAXIMUM CABIN DEW POINT (MDAC SAMSP IS 16°C, SPACELAB IS 11°C)

APPROACH:

- INTEGRAL THERMAL/METEOROID BLANKET ON EXTERIOR OF STRUCTURE
- USE CURRENT SPACELAB LAYUP AS REPRESENTATIVE DESIGN:

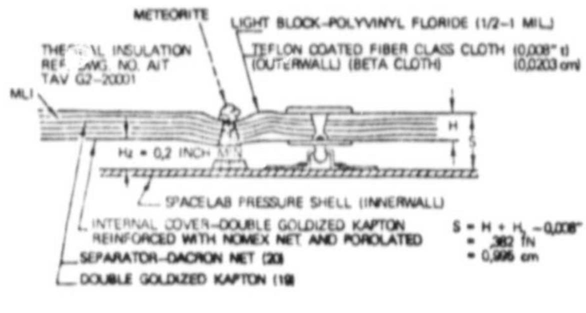
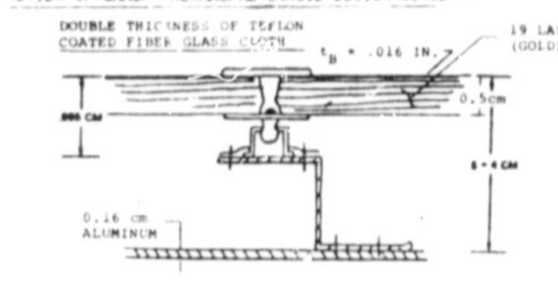


FIGURE 71

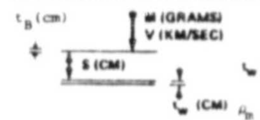
THERMAL PROTECTION APPROACH

REVIEW OF SAMSP THERMAL/METEOROID DESIGN CONCEPT:



MODIFIED SPACELAB DESIGN PROVIDES 10 YEAR PROTECTION AT Po = .95 FOR FOUR 3-SEGMENT MANNED MODULES

METEOROID PROTECTION RELATIONSHIP:



$$t_w = \frac{0.056\,(\rho_m \rho_B)^{1/6}\, M^{1/3}\, V}{S^{1/2}} \left(\frac{70000}{\sigma_y}\right)^{1/2}$$

ρ_m = METEOROID DENSITY (g/CM^3) = 0.5 gm/cm^3

ρ_B = BUMPER DENSITY (g/CM^3)

σ_y = YIELD STRENGTH OF WALL (PSI)

t_B = BUMPER THICKNESS $\geq$ .04 METEOROID DIAMETER

V = METEOROID VELOCITY ≈ 20 km/SEC

M = METEOROID MASS (gm)

S = STANDOFF DISTANCE (cm)

FIGURE 72

METEOROID PROTECTION APPROACH

The analytical relationship in Figure 72 is from Ref. 13. The expression gives pressure vessel wall thickness required to avoid penetration of a meteoroid to such a depth that spalling of the back surface occurs. The criteria for validity of that expression are that the bumper thickness be greater than or equal to 0.04 x meteoroid diameter and also that the spacing between the bumper and wall be less than or equal to 30 x meteoroid diameter. No improvement in meteoroid protection is obtained when greater spacings are used. Based on the blanket layup, the standoff distance provided by the deployable truss structure, and the bladder layup, the meteoroid penetration probabilities were calculated using the meteoroid distribution curve given in the Requirements (Section 3.2) and the equation given in Figure 72. It was necessary to express the meteoroid thermal blanket thickness in terms of an equivalent aluminum sheet thickness in order to use this equation. Based on the studies of Ref. 8, the thermal meteoroid blanket was estimated to have an equivalent aluminum thickness of 0.13 cm. The wall properties were taken to be those of the Kevlar-49 fabric and did not include the other layers in the layup (which have much smaller yield strengths). It was calculated that the habitat module pressure bladder and meteoroid blanket will stop a 3.25 cm diameter meteoroid. The external surface area of the habitat module exposed to meteoroids is 786 m^2. Entering Figure 44 with a 3.25 cm diameter meteoroid the cumulative flux for all sizes larger is approximately 2×10^{-8} impacts/m^2-year. With that flux and a duration of ten years, using the 786 m^2 exposed area, the probability of no penetrations is 0.998. This very high value illustrates one of the benefits of the geometry for the deployable volume.

The Figure 44 debris flux was also considered and the debris penetration characteristics of the habitat were evaluated. The debris velocity is approximately 10 km/sec compared to the much higher meteoroid velocity of 20 km/sec. However, since debris is largely fragments of spacecraft the density of aluminum (2.77 gm/cm^3) should be representative, much greater than the 0.5 gm/cm^3 of meteoroids. The Figure 72 equation and its criteria for applicability also predict a debris object of 3.25 cm diameter will be stopped by the deployable habitat design. From the 1978 debris model the probability of the habitat encountering a debris fragment of this size or larger during 10 years was calculated to be 0.05; therefore, the probability of no penetrations is approximately 0.95. If a space radiator were added on the outside of the thermal meteoroid blanket additional improvement in debris protection would result. A typical radiator is approximately 0.5 gm/cm^2 in weight (1 lb/ft^2). Adding the equivalent aluminum sheet thickness of 0.18 cm resulting from this radiator weight to the blanket equivalent thickness of 0.13 cm results in the capability of the combination stopping a debris fragment up to about 8 cm diameter. The result is now improved to where the probability of no debris penetration for ten years is increased to about 0.975 and further emphasizes the advantage of the deployable volume approach for both meteoroid and debris protection. The necessity of deploying separate bumpers for debris protection, as was done in Ref. 8, is completely avoided.

4.3.3 Radiation Protection Analyses

As given in the Requirements Section Table 8, it was seen that a shielding of 0.5 to 1.3 gm/cm^2 is necessary to protect the crew against space radiation over a 180 day period. For the habitat module in the V_1 area (outside the inner core), radiation protection is obtained from the bladder material, the exterior thermal meteoroid blanket, and to some extent, the deployable truss structure. In addition extra protection is provided if a radiator is installed on the outer diameter. The thermal/meteoroid blanket provides about 0.05 gm/cm^2 of mass; the truss structure provides an equivalent of about 0.06 gm/cm^2 and the bladder provides about 0.6 gm/cm^2. The resulting total protection for occupants of Volume V_1 is about 0.74 gm/cm^2. With the radiators added to the exterior of the habitat module, the protection is increased to 1.21 gm/cm^2 in the area of the radiators. The hangar module with its slightly less thick bladder provides a protection level of about 0.54 gm/cm^2. It is not expected that a significant portion of the external area of the hangar module would be covered with radiators. These levels of radiation protection should be adequate for missions at the lower inclinations and altitudes, such as the reference mission for the SAMSP. For a more severe environment an extra layer of material, perhaps in the form of a blanket, could be added on the outer portion of the structure or the outer portion of the bladder.

4.3.4 Heat Rejection

An exterior area of about 500 m^2 is available on the outer diameter of the cylindrical section of the habitat. If this entire area were covered with radiators each with a total emissivity of 0.8, a fin effectiveness of 0.9, a mean radiating temperature of 70°F, and a environmental sink temperature of 0°F, if would be possible to reject about 65 kW. Because of the cutouts necessary for the four docking ports on the cylindrical section, somewhat lesser area would actually be available. An upper practical limit of 50 kW heat rejection for the temperatures cited above is probably reasonable. With the deployable habitat concept presented in this report the radiators would be added after deployment of the volume. A candidate type of radiator would be a constructable radiator, which consists of a heat pipe embedded in a radiating fin. Current work sponsored by NASA-JSC indicates that lengths up to about 60 ft are practical for constructable radiators with widths of about 1 to 2 ft. These constructable radiators plug into a contact heat exchanger interface at the ends of the panels. A constructable radiator system can be envisioned which appears as a series of slats laying on the outer diameter of the cylindrical portion of the habitat and oriented parallel to its axis. Based on prototype work completed on constructable radiator interfaces, it would be feasible to install these radiators using the RMS subsequent to deployment of the deployable volume.

5.0 SPECIAL TECHNOLOGY NEEDS FOR DEPLOYABLE VOLUMES

Three areas of technology needs were identified: docking interfaces, soft goods and connectors. Table 15 shows two docking interface needs which were determined to be required in the deployable volume study. During buildup a rotating joint or indexing joint at the docking interface

TABLE 15

SPECIAL TECHNOLOGY NEEDS - DOCKING INTERFACES

1. **Rotating Joint at Docking Interface Between Habitat and Station**

   . ±180° rotation, powered and rotationally positioned
   . hollow core for crewman passage and temporary utilities umbilical
   . withstand interface loads at docking adapter due to on-orbit accelerations and berthing

2. **Offset Boom Interfacing Orbiter to Station for Access to Hangar Buildup**

   . mechanical and electrical signal interface
   . may require deployment/retraction to permit docking and positioning
   . withstand interface loads due to docking and on-orbit accelerations

between the habitat and Station will be required for holding and positioning the deployable volume. In addition, an offset docking boom will be required during hangar buildup to allow access and positioning of the hangar with the Shuttle docked to the Station. Table 16 indicates some of the needs for soft goods. Properties and life characteristics of candidate bladder materials

TABLE 16

SPECIAL TECHNOLOGY NEEDS - SOFTGOODS

Properties of Candidate Bladder Materials

- structural and thermal
- life, environmental degradation
- flexure characteristics
- gas sealing
- meteoroid and debris penetration

Folding and Fabrication Characteristics for Shaped (thermal/insulation blankets and bladder)

- patterning
- prototyping for folding and deployment of softgoods attached to truss

Seals Development

- flexible seals for bladder interface with docking port - IVA installation
- seals for hangar ring

need to be developed, as well as the folding and fabrication characteristics for the shaped configurations that have been developed. In addition flexible seals will be needed for interfacing the habitat bladder with the docking port and for sealing the hangar ring area. Table 17 summarizes needs for connectors. Since the V_1 of the habitat will be assembled on orbit, with partially built up utilities, it will be necessary to install numerous cables,

TABLE 17

SPECIAL TECHNOLOGY NEEDS - CONNECTORS

Habitat

. Installation of Electrical Cables, Air Ducting and Liquid Lines in Deployed Volume

. Optimize for Ease of Installation of Utilities at Buildup and Subsequent Reconfiguration

Hangar

. Refueling, Pressurized or Vacuum Environment

- containment of hazardous spills

air ducting and liquid lines. Connectors for rapid, sure, and easy installation will be required. In the use of the OTV hangar it is expected that refueling and other hazardous fluid transfers will require the development of a technique for containment of hazardous spills.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This section presents conclusions relative to the ground test article design and the Part 2 deployable volume study. Part 1 conclusions were summarized in Section 2.0 and presented in detail in Ref. (3).

6.1 GROUND TEST ARTICLE DESIGN

1. Layout drawings have been completed for the BADF ground test article. The article meets all the requirements of the NASA specifications.
2. Simple intefaces have been achieved with existing NASA-MSFC air bearing facility frictionless platform, and a minimum of changes will be required to accommodate the Biaxial Double Fold test article.
3. While the ground test article is designed for testing on an air bearing platform, it is also suitable for modification for neutral bouyancy testing. Modifications to the springs in the vertical struts and the addition of floatation chambers would be required.
4. The basic ground test article is also suitable for Orbiter flight test experiments with some modifications. It would be highly desirable to increase the stiffness at partial deployment to accommodate potential Shuttle accelerations of 0.04 g. This can be accomplished by using localized deployment motors on 8 nodes with short cable runs, fabricating the truss from graphite/epoxy, and beefing up the diagonals.

6.2 DEPLOYABLE VOLUMES

1. A rigid central core concept has been developed which will minimize EVA requirements during buildup. In addition this concept provides a rigid backbone for interface with the Orbiter during launch. For the habitat the concept utilizes a central core module which is pressurizable and which contains modularized equipment. It interfaces with a pressurized cargo module for delivery of additional modularized equipment. Shirtsleeve transfer and buildup is provided, and very little EVA is required. For the hangar the centralized core provides structural support and storage during launch, but does not provide pressurization. The concept selected also reduces EVA and RMS requirements for the hangar.

2. A large deployable habitat module can be delivered and erected in one Shuttle flight, and completely outfitted with an additional 1-2 Shuttle flights. The 13.5m (44.2 ft) diameter habitat would be about 1130 m^3 (40,000 ft^3) in volume and would accommodate up to twelve men.
3. A 10.1m (33.2 ft) diameter by 23.1m (75.8 ft) deployable OTV hangar can be delivered and assembled in one Shuttle flight. This hangar is suitable for pressurized or unpressurized OTV operations and will accommodate both near term earth-based OTV designs as well as future reusable space-based concepts. Adequate volume is provided for the OTV, work platforms, and spares storage.
4. The BADF structure provides best overall compatibility with deployable volumes, and permits integral attachment and deployment of the external thermal/meteoroid blanket and the pressure bladder.
5. The basic deployable truss structure concept with a bladder on the inside and a thermal/meteoroid blanket on the outside inherently provides excellent meteoroid and debris protection. For the habitat module a probably of no meteoroid penetration of 0.998 for 10 years is provided. A 3.25 cm debris fragment will be stopped, yielding, based on the 1978 debris model, a probablity of no debris penetration of 0.95 for 10 years. With the addition of radiators to the exterior of the habitat module, the area shielded increases in debris protection to a probability of 0.975 for no penetration for 10 years. The basic design of the habitat also provides radiation shielding of about 0.7 gm/cm^2 which is suitable low inclination (LEO) missions for a crew rotation period of up to 180 days. It is feasible to add additional shielding if more severe missions are required.

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